

AD-A047 918

GENERAL RESEARCH CORP SANTA BARBARA CALIF

THE ROSCOE MANUAL. VOLUME 20 - SATELLITE COMMUNICATION MODEL.(U)

F/6 17/2.1

JAN 77 H S OSTROWSKY, J R GARBARINO

DNA001-74-C-0182

UNCLASSIFIED

CR-1-520-VOL-20

DNA-3964F-20

NL

| OF |
AD
A047918



END
DATE
FILMED

1 -78

DDC

AD-E300 046
DNA 3964F-20

AD A047518

THE ROSCOE MANUAL.

Volume 20-Satellite Communication Model.

General Research Corporation
P.O. Box 3587
Santa Barbara, California 93105

January 1977

Final Report.

CONTRACT No. DNA 001-74-C-0182

APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION UNLIMITED.

DNA, SBIE

THIS WORK SPONSORED BY THE DEFENSE NUCLEAR AGENCY
UNDER RDT&E RMSS CODES B322074464 S99QAXHC06428 AND
B322075464 S99QAXHC06432 H2590D.

H. S. / Ostrowsky, J. R. / Garbarino
J. J. / Baltes

Prepared for

Director
DEFENSE NUCLEAR AGENCY
Washington, D. C. 20305

AD NO.
DDC FILE COPY

DDC
RECEIVED
DEC 22 1977
B

102 754

Destroy this report when it is no longer needed.
Do not return to sender.



UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER DNA 3964F-20 ✓	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) THE ROSCOE MANUAL Volume 20—Satellite Communication Model		5. TYPE OF REPORT & PERIOD COVERED Final Report
7. AUTHOR(s) H. S. Ostrowsky J. R. Garbarino J. J. Baltes		6. PERFORMING ORG. REPORT NUMBER CR-1-520, Vol. 20 ✓
9. PERFORMING ORGANIZATION NAME AND ADDRESS General Research Corporation P.O. Box 3587 Santa Barbara, California 93105		8. CONTRACT OR GRANT NUMBER(s) DNA 001-74-C-0182 ✓
11. CONTROLLING OFFICE NAME AND ADDRESS Director Defense Nuclear Agency Washington, D. C. 20305 ✓		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Subtasks S99QAXHC064-28 and S99QAXHC064-32
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE January 1977
		13. NUMBER OF PAGES 72
		15. SECURITY CLASS (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES This work sponsored by the Defense Nuclear Agency under RDT&E RMSS Codes B322074464 S99QAXHC06428 and B322075464 S99QAXHC06432 H2590D.		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Nuclear Effects Propagation Radar Satellite Communication Computer Program Simulation		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The ROSCOE computer code is designed specifically to be the "laboratory standard" for evaluating nuclear effects on radar and optical sensors. The program provides a means for (1) evaluating radar acquisition, discrimination, and tracking performance in a nuclear environment; (2) estimating various radar and optical propagation error sources; and (3) computing specific phenomenological data. Volume 20 of this series describes ROSCOE's satellite communication model.		

DD FORM 1 JAN 73 1473

EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

CONTENTS

SECTION		PAGE
1	INTRODUCTION	3
2	THE FUNDAMENTAL PARAMETER	5
3	PROBABILITY OF ELEMENT ERROR	8
4	AMPLIFICATION OR REGENERATION	10
5	PROPAGATION AND THE ENVIRONMENT	12
	5.1 Nuclear and Ionospheric Effects	12
	5.2 Dispersive Losses	13
	5.3 Tropospheric and Celestial Effects	15
6	SCINTILLATIONS AND STRIATIONS	18
	6.1 Phase Scintillations	18
	6.2 Amplitude Scintillations	27
7	INPUTS	33
8	OUTPUTS	39
	REFERENCES	41
APPENDIX A	COMMUNICATIONS DATASETS	43
APPENDIX B	MODIFICATIONS TO PROGRAM STRUCTURE	49

ACCESSION for		
NTIS	White Section	<input checked="" type="checkbox"/>
DDC	Buff Section	<input type="checkbox"/>
UNANNOUNCED		<input type="checkbox"/>
JUSTIFICATION		
BY		
DISTRIBUTION/AVAILABILITY CODES		
Dist.	AVAIL.	and/or SPECIAL
A		

1 INTRODUCTION

The ROSCOE Communication Model is a computer program that combines the ROSCOE nuclear phenomenology and propagation modules with a package that simulates a communication link and computations specific to four types of digital modulation. These are: binary frequency shift keying (FSK), both coherent and non-coherent, and binary phase shift keying (PSK), both coherent and differentially coherent. These four were selected because they are applicable to a large number of satellite communication systems, both current and future, and because mathematical models of these processes are readily available in the literature.

In addition to the choice of modulation, the user has a wide range of options in setting up the link parameters. He may select antenna types, beam patterns and gains, RF frequencies, bandwidths, transmitter powers, receiver noise factors, line losses, and bit rates. He may select either plain amplification or regeneration (i.e., demodulation and retransmission) of the signal at the satellite transponder. The "ground" stations may be either stationary or mobile, and may be airborne. If (as is usually the case) the receiver filters are not perfectly matched to the signals, the appropriate mismatch losses will be calculated. If one or more of the antennas are phased arrays, the off-boresight scanning loss will be computed. All of these are applicable individually to the uplink and downlink and separately to each antenna, transmitter, and receiver in the system.

The environmental effects which are modeled include losses due to absorption (both nuclear-induced and ambient), refractive beam-spreading, and dispersion (additional filter mismatch at the receivers), external noise due to nuclear sources, atmospheric absorptive effects, galactic sources, the earth, and the sun. Also included are correlated amplitude and phase scintillations due to striations. The amplitude scintillations (fades) affect all types of signal modulation through the signal-to-noise ratios at the receivers; the specific effects of the phase scintillations

on demodulator performance are considered in detail for the PSK modulations. The most complete model is available for the case of DPSK, where the user can also choose either to average the effect of the instantaneous phase scintillations over the ensemble of possible phase errors or to select a (correlated) random sample from this ensemble at each calculation.

This memorandum briefly describes the mathematical models contained in the ROSCOE Communication Model. Although the sources are indicated whenever possible, no attempt has been made to derive or justify these formulae and algorithms. To do so would have multiplied the length of this document several fold.

2 THE FUNDAMENTAL PARAMETER

The fundamental parameter which can be used to determine the properties of a digital communication link is γ , the ratio of the total average received energy per signal element to the noise power per unit bandwidth:

$$\gamma = E/N_0 \quad (1)$$

This can also be expressed in terms of other important properties of the link by noting that

$$\gamma = \left(\frac{S}{N}\right) \tau B \equiv \left(\frac{S}{N}\right) \frac{B}{\rho} \log_2 M \quad (2)$$

where $\left(\frac{S}{N}\right)$ = received signal-to-noise ratio

τ = length of a signal element, seconds

B = receiver IF bandwidth, Hz

ρ = data transmission rate, bits/second

M = number of possible waveforms per transmission: for an M -ary system,

$$\rho \equiv \frac{\log_2 M}{\tau} \quad (3)$$

The dependence of γ on the basic system and propagation parameters can be made explicit by recalling that

$$\left(\frac{S}{N}\right) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 R^2 L_L L_1 L_2 k B (T_n + T_x)} \quad (4)$$

where

P_t = total average radiated RF power at transmitting antenna

G_t = gain of transmitting antenna

G_r = gain of receiving antenna

λ = wavelength of transmitted carrier

R = distance between transmitting and receiving antennas

L = total propagation loss between transmitting and receiving antennas

L_1 = system loss between transmitter and transmitting antenna

L_2 = line loss between receiving antenna and receiver

k = Boltzmann's constant

B = receiver IF bandwidth

T_n = nominal system noise temperature

T_x = receiver noise temperature due to all external noise sources

The two temperatures appearing in this equation are further defined by

$$T_n = T_R + \left(\frac{L_2 - 1}{L_2} \right) T_p = (\overline{NF} - 1) T_o + \left(\frac{L_2 - 1}{L_2} \right) T_p \quad (5)$$

and

$$T_x = \frac{T_A}{L_2} \quad (6)$$

where

T_R = receiver noise temperature

T_p = physical temperature of antenna

\overline{NF} = receiver noise figure

T_o = reference temperature ($T_o = 290^\circ\text{K}$)

T_A = antenna noise temperature due to all external noise sources

Finally, it is assumed that both link antennas are steerable reflectors pointing directly at one another. If either of the antennas is a phased array, then Eq. 4 must be altered by replacing the appropriate gain factor, G , by $G_o \cos \theta$, where G_o is the boresight gain of the phased array antenna and θ is the current off-boresight beam pointing angle.

All of this excruciating detail has been given here because this set of equations determines how the communication system and the propagation environment interact to produce the fundamental parameter. All propagation effects can be described by stating how they affect either L or T_A , and any additional losses caused by demodulator performance in an imperfect environment are functions of the received value of γ before demodulation.

The present version of the ROSCOE Communication Model considers binary systems only. Thus $M \equiv 2$ and $\rho \equiv 1/\tau$. Furthermore, it might be worth noting that the time-bandwidth product is generally a number of the order of unity: $\tau B \sim 1$.

3 PROBABILITY OF ELEMENT ERROR

The measure of overall system performance used in the ROSCOE Communication Model is P_e , the probability of element error. Recall that a digital signal consists of a sequence of symbols, each of which is made up of a sequence of elements. For each received element (including spaces) in the message the receiver makes a judgment, based on tests which are specific to the particular signaling mode being used, as to which element was transmitted. The probability that the receiver will make a wrong judgment on a given element is P_e . If $M > 2$ each element conveys more than one bit of information, so in general P_e is not the same thing as the probability of bit error. For $M = 2$ the distinction vanishes.

Of course, appropriate coding can be used to reduce the incidence of message errors even when P_e is not insignificant, but coding is a complex subject with which we shall not be concerned here. The element error probability, P_e , is the final output of each calculation in the Communication Model.

For each of the binary digital modulation modes contained in the present ROSCOE model, there is a simple closed-form expression for P_e as a function of γ alone, which can be found in standard texts on communication theory such as Ref. 1. These are:

Coherent Phase-Shift Keying (CPSK)

$$P_e = \frac{1}{2} \operatorname{erfc} \sqrt{\gamma} \quad (7a)$$

Differentially Coherent Phase-Shift Keying (DPSK)

$$P_e = \frac{1}{2} \exp(-\gamma) \quad (7b)$$

Coherent Frequency-Shift Keying (CFSK)

$$P_e = \frac{1}{2} \operatorname{erfc} \sqrt{\frac{\gamma}{2}} \quad (7c)$$

Non-Coherent Frequency-Shift Keying (NFSK)

$$P_e = \frac{1}{2} \exp\left(-\frac{\gamma}{2}\right) \quad (7d)$$

where $\operatorname{erfc}(x) \triangleq 1 - \operatorname{erf}(x)$

Since these simple expressions involve only γ , they obviously cannot account for any possible dependence of P_e on other variables. As such they are strictly valid only for isolated single elements in an environment which is changing very slowly (or not at all) relative to the element length. For more rapid, but still sufficiently slow, amplitude variations (slow fading) they can be modified by integrating over the probability distribution function in γ , if known. The resulting expressions would then represent an average P_e over a time period encompassing many fades, and would no longer be appropriate for a deterministic single-pulse model. When phase fluctuations become significant, as is usually the case when propagation through a striated medium occurs, even more complicated modifications are necessary. For PSK systems the appropriate modifications have been found in the literature and incorporated into the ROSCOE model. For FSK, such modifications have not been available and are not included.

It should be emphasized that Eqs. 7 are useful starting points for further analysis, and provide good baseline computations even in unmodified form.

4 AMPLIFICATION OR REGENERATION

Satellite communication is almost always a process in which two different stations on (or near) earth contact one another by way of a satellite station as intermediary. The complete path of communication, then, involves both an uplink and a downlink, each affected by its individual propagation environment. Each link therefore will have its own value of P_e which will, however, have only a potential existence unless the signal is actually demodulated upon reception at the link terminus.

The ROSCOE Communication Model calculates the values of P_e for the uplink and the downlink and also for the total up-and-down communication path. The way in which the total P_e for the received signal is determined depends on how the uplink signal is processed at the satellite before retransmission to earth. There are fundamentally two ways this can be done: amplification or regeneration. The ROSCOE model permits the user to select one or the other of these alternatives; they are, of course, mutually exclusive in any given transmission.

The satellite transponder can amplify and retransmit the incoming signal without ever demodulating it. In that case, neither the potential $P_e(\text{up})$ nor the potential $P_e(\text{down})$ have an actual existence; only the $P_e(\text{total})$ exists and is calculated by means of an appropriate equation (e.g., Eqs. 7) as a function of $\gamma(\text{total})$. Letting γ_u and γ_d be the fundamental parameters for the uplink and downlink, respectively, it is not difficult to show that

$$\gamma(\text{total}) = \left[\frac{B_u \tau_u}{B_d \tau_d} \frac{1}{\gamma_u} + \frac{1}{\gamma_d} \right]^{-1} \quad (8)$$

where $B_u \tau_u$ and $B_d \tau_d$ are the respective time-bandwidth products.

On the other hand, if regeneration is used, then the satellite transponder first demodulates the incoming signal, then imposes an equivalent modulation on a new signal which is transmitted down to earth. Now, both $P_e(\text{up})$ and $P_e(\text{down})$ have concrete existence and meaning, and the value of $P_e(\text{total})$ must be calculated by carefully combining them in proper fashion. The correct combination depends on the value of M for the system; since we are concerned at present only with binary systems, it is easily seen that

$$P_e(\text{total}) = P_e(\text{up}) + P_e(\text{down}) - 2P_e(\text{up}) \cdot P_e(\text{down}) \quad (9)$$

5 PROPAGATION AND THE ENVIRONMENT

On its way from transmitter to receiver the signal is affected or acted upon by the environment through which it propagates. These effects show up as loss factors to be multiplied into L , as antenna temperatures to be added to T_A , and as phase fluctuations which affect some types of communication systems in more complicated ways. Some are specifically related to the nuclear bursts and associated phenomena: smoothly-varying absorption (appearing as a loss factor L_A), fluctuating absorption due to striations (appearing as correlated fades changing the value of γ), beam-spreading loss (L_B), dispersive loss (L_D), fireball noise (T_F), and phase scintillations with variance μ^2 and decorrelation time τ_D . Some are related to the natural environment: tropospheric absorption (L_T), ionospheric absorption (included as part of L_A), noise due to atmospheric oxygen and water vapor (T_T), solar radiation (T_S), galactic radiation (T_G), and the earth's effective radiating temperature (T_E). All of these will be described briefly in the following subsections.

5.1 NUCLEAR AND IONOSPHERIC EFFECTS

A stochastic calculation of the effects of the ionosphere and any nuclear fireballs or debris regions on signals propagating through them may be thought of as the pivotal element in the ROSCOE Communication Model, comprising as it does the meeting place of the nuclear phenomenology, signal propagation, and system aspects of the model. This is not the place, however, to discuss the details of these calculations, which may be found elsewhere.² ROSCOE contains modules that calculate the electron density along the path; the locations, directions, size and density distributions, and motions of striated regions; and refractive propagation through smooth or striated media. Combining these data with the locations, properties, and motions of the transmitting and receiving antennas, it is possible to compute values for the simple absorption (L_A), beam-spreading loss (L_B), RMS phase scintillations (μ), scintillation decorrelation time (τ_D), and integrated electron density (I_E) along the path between these antennas at any given time. It should be noted

that this calculation includes the effects of both dispersive time delays and dog-leg multipaths on the phase error variations, and therefore differs from some of the simpler models found in the literature, which include only the former.

Another calculation based on the nuclear phenomenology provides a value for the effective integrated fireball thermal noise temperature (T_F) as seen by the receiving antenna for the given link. This model involves the sizes, shapes, temperatures, emissivities, motions, and locations of all contributing fireballs, the attenuation along the paths connecting them to the receivers, and the appropriate beam-filling factors related to the size, shape, and location of the antenna beam.

5.2 DISPERSIVE LOSSES

When propagating through an ionized medium, a time-limited signal experiences dispersion, which alters its spectral content. If such a signal is then put through a receiver filter which is matched to the original transmitted form, there will be a mismatch and consequent energy decrease which we can express as a dispersive loss. Two distinct losses of this type are included in ROSCOE by means of simplified but generally adequate models.

The original signal element is idealized as a rectangular pulse of length τ , and the receiver filter is idealized as a rectangular band-pass filter of bandwidth B . Even if there is no dispersion, such a filter is not really a match to the signal, so there will always be some mismatch loss, L_F . For PSK modulations this primary mismatch loss is represented by $L_F = 1/\eta_0$, where η_0 is defined by Eq. 20' in Sec. 6.1. The analysis leading up to the definition of η presented in that section is pretty complicated. For FSK modulations, a simpler form of analysis is used which in effect considers isolated single signal elements and ignores the alterations due to coupling of quasi-random trains of such pulses in real signals. The primary mismatch loss can then be shown to be given by

$$L_F = \frac{\pi}{2} \frac{x}{[Si(x)]^2} \quad (10)$$

where

$$x \equiv \frac{\pi}{2} \tau B \quad (11)$$

It is well known that the loss function of Eq. 10 has a broad minimum at $x \approx 2.2$ (equivalent to $\tau B \approx 1.4$), at which point the mismatch loss is approximately $L_F \approx 1.2$ (0.8 dB). If the filter bandwidth differs from this optimum value the loss factor will be accordingly greater.

If in addition the signal experiences dispersion through traversal of an ionized **region characterized by a total integrated electron density** of I_E , then there is an additional dispersive loss. By making a quadratic approximation to the dispersion function, it is not difficult to find an expression for this dispersive loss factor; it turns out to be

$$L_D = \frac{\pi}{2} \frac{x}{L_F} \frac{1}{G(a, x)} \quad (12)$$

where

$$G(a, x) \equiv \left| \int_0^x \frac{\sin \xi}{\xi} \exp\left(i \frac{a \xi^2}{4}\right) d\xi \right|^2 \quad (13)$$

and

$$a = \frac{0.06 I_E^{1/2}}{\tau f^{3/2}} \quad (14)$$

f being the carrier frequency (Hz). This approximation is used in the ROSCOE model.

5.3 TROPOSPHERIC AND CELESTIAL EFFECTS

As the signal traverses the troposphere, it is subject to a loss, L_T , due to absorption by oxygen and water vapor. The downlink antenna also receives a noise component, designated by T_T , due to reradiation by oxygen and water vapor. The calculation of these two effects is based on curve fits to empirical data on these two phenomena, as functions of antenna elevation angle and carrier frequency. These models were taken directly from the SATL code,³ and will not be reproduced here.

There are also noise components, in one or the other receiving antenna, due to "celestial" sources, namely the sun, the galactic background, and the earth as a radiator. For most frequencies of interest to satellite communication systems these are relatively small temperature increments, and their values can only be approximated since conditions vary with time and location. Nevertheless, approximations to these three antenna temperatures have been included in ROSCOE in the interest of completeness.

The uplink receiving antenna, looking down upon the earth, does not see the sun or the galaxy. It sees the earth's surface, radiating a noise whose power can be related to an antenna temperature, T_E . This noise, which comes originally from the surface but is transferred to the satellite antenna by way of reradiation through the atmosphere, should be a function of frequency f . However, we have not been able to find data on this phenomenon, so in the present ROSCOE model we have substituted a constant temperature, approximately that of the upper atmosphere, namely $T_E = 250^\circ$. If a more realistic model should come to our attention it can easily be substituted for this approximation, which in the meanwhile we retain.

The downlink receiving antenna, looking up, receives radiation from the general galactic background, and from the sun if some portion of the antenna's mainlobe intersects the solar disk. The ROSCOE models for these phenomena are taken from a paper by Hogg and Mumford.⁴

The received cosmic noise from the galaxy appears as from a continuous source covering a large area of the sky, but having an intensity which varies with angular distance from the galactic center as well as with the carrier frequency. There are also, of course, localized cosmic sources (radio stars, quasars, etc.), but it would not be practical to include a map of their locations in the ROSCOE model, so they are ignored. Similarly, the variations in galactic noise temperature with celestial latitude and longitude involve more calculational complexity than is warranted by the importance of the result. This is replaced by an approximate average temperature which is a function only of the frequency:

$$T_G \approx \frac{2.6 \times 10^{19}}{f^2} \text{ } ^\circ\text{K} \quad (15)$$

The noise temperature of the sun depends somewhat on the time within the sunspot cycle, as well as localized phenomena such as flares. Ignoring this, we will use the mean temperature of the quiet sun, which is a function only of frequency. Empirical data are well fitted by the following approximations:

For $f < 250 \text{ MHz}$ or $f > 35 \text{ GHz}$,

$$T_{\odot} \approx \frac{2 \times 10^{14}}{f} \text{ } ^\circ\text{K} \quad (16a)$$

For $250 \text{ MHz} \leq f \leq 35 \text{ GHz}$,

$$T_{\odot} = \frac{2 \times 10^{14}}{f} \left\{ 1 + \frac{1}{2.3} \sin \left[2\pi \log 2.6 (f \times 10^{-9} - 0.10) \right] \right\} \quad (16b)$$

the frequency f being given in Hz.

Unless the solar disk completely fills the radar beam, however, this is not the antenna temperature seen by the receiver. In order to find T_S it is necessary to multiply T_{\odot} by a beam-filling factor which depends on the size and location of the antenna beam relative to the sun. If the solar disk is completely outside the mainlobe, the beam-filling factor is approximated by zero; otherwise, it is computed by a straightforward but complicated little algorithm which need not be reproduced here.

6 SCINTILLATIONS AND STRIATIONS

If the environment remains constant or varies slowly in a smooth manner, the computations already described are sufficient to complete the model. The presence of striations and the attendant scintillations introduces new difficulties which must be dealt with. Propagation through a region of field-aligned striations is known to introduce phase fluctuations, often of considerable magnitude. At a sufficient distance from the striated region ("phase screen") these can add up to produce significant amplitude fluctuations as well, although it is not uncommon to find little or no amplitude fluctuation at a place where the phase is scintillating greatly.

This is not the place to go into the extensive literature on the origins and properties of these scintillations. In any case there is not yet a general consensus on this subject, and the debate in the literature continues to be sometimes heated. What is needed for ROSCOE is a model which is in good agreement with experimental data or theoretical findings for such cases as are widely acceptable by the community, which produces reasonable results for cases where understanding remains obscure, and which passes smoothly from one regime to the other. It is desirable to make as few ad hoc assumptions as possible.

Let us consider now the modeling of the effects of phase and amplitude scintillations on the digital communication systems.

6.1 PHASE SCINTILLATIONS

The ROSCOE propagation model produces a description of phase scintillations which is stochastic rather than deterministic. The correlated phase fluctuations at the receiving antenna are represented by a zero-mean, stationary Gaussian process with variance μ^2 and decorrelation time τ_D . From these two quantities it is possible to build up a picture of how a PSK communication system will be affected by the phase scintillations. This analysis has been very well described in two ESL

reports,^{5,6} upon which this part of the ROSCOE model is primarily based. Although we will quote the needed results in this subsection, the reader is referred to the original reports for details.

As far as FSK communications systems are concerned, we have no information on possible effects of phase scintillations on them, and the ROSCOE model does not contain any such effects.

Returning to the statistical model presented in the ESL reports, it is assumed that the phase scintillation process is represented by a first-order Butterworth power spectral density (PSD) function:

$$S_{\psi}(\omega) = \frac{2\mu^2/\tau_D}{\omega^2 + (1/\tau_D)^2} \quad (17)$$

corresponding to an exponential autocorrelation function of the form

$$R_{\psi}(t) = \mu^2 e^{-|t|/\tau_D} \quad (18)$$

The two-sided PSD of the PSK modulated signal with the random phase scintillations imposed on it is called $S_s(f)$ and is given by a complicated expression which we shall not attempt to reproduce here. When the signal is passed through the receiver's band-pass filter (of bandwidth B), it can be shown that the signal-to-noise ratio after filtering is reduced by a factor η as compared to its value prior to the filter. The factor η is defined by

$$\eta(\tau_B, \tau/\tau_D, \mu) \equiv \frac{4}{A^2} \int_{f_o - B/2}^{f_o + B/2} S_s(f) df \quad (19)$$

where A is the amplitude and f_o the frequency of the signal carrier. This factor η is quite important for the rest of this analysis. In addition to expressing the SNR loss due to IF filtering prior to demodulation, we shall also see it appear in the analysis of the performance of a CPSK demodulator.

With a considerable amount of effort, the integral in Eq. 19 can be reduced to a series whose form, however, is not particularly transparent. It is:

$$\eta(\tau B, \tau/\tau_D, \mu) = \frac{2}{\pi} e^{-\mu^2} \sum_{n=0}^{\infty} \frac{\mu^{2n}}{n!} f_n(\tau B, \tau/\tau_D) \quad (20a)$$

where

$$f_n \equiv \frac{\left[\pi B \tau \cos(\pi B \tau) + \frac{n \tau}{\tau_D} \sin(\pi B \tau) \right] e^{-n \tau / \tau_D} - \pi B \tau}{r_n^2} + \sum_{m=1}^{\infty} \frac{(-1)^m r_n^m \sin(m \theta_n)}{m \cdot m!} \quad (20b)$$

with

$$r_n \equiv \left[(\pi B \tau)^2 + \left(n \frac{\tau}{\tau_D} \right)^2 \right]^{1/2} \quad (20c)$$

and

$$\theta_n \equiv -\tan^{-1} \left(\pi B \tau \cdot \frac{\tau_D}{n \tau} \right) \quad (20d)$$

As may well be imagined, the creation of a computer subroutine to evaluate this function η was a rather delicate matter.

It should be noted that when there are no scintillations ($\mu = 0$ or $\tau_D \rightarrow \infty$) the function η does not become unity, but takes on the value

$$\eta_0 = \frac{2}{\pi} \left[S_i(\pi B\tau) - \frac{1 - \cos(\pi B\tau)}{\pi B\tau} \right] \quad (20')$$

We have just seen that when PSK modulation is being used the signal-to-noise ratio, and hence also the fundamental parameter γ , prior to demodulation is reduced by the factor η . Therefore, when regeneration is being employed, the values of γ_u and γ_d (the subscripts standing for "uplink" and "downlink," respectively) must be replaced by $\eta_u \gamma_u$ and $\eta_d \gamma_d$ when evaluating the error probabilities $P_e(\text{up})$ and $P_e(\text{down})$.

When regeneration is not being employed, we must first determine the values of μ_T and τ_{DT} for the total composite path consisting of uplink and downlink (the subscript T standing for "total"). For the variance μ^2 the correct formulation is obvious:

$$\mu_T^2 = \mu_u^2 + \mu_d^2 \quad (21)$$

For the decorrelation time, however, the appropriate combination can only be estimated; we use the approximation

$$\tau_{DT} = \left[\frac{1}{\tau_{Du}} + \frac{1}{\tau_{Dd}} \right]^{-1} \quad (22)$$

We can now use these values to compute the factor η_T for the combined two-way path. Finally, it can be shown that the total received γ before demodulation at the ground receiver is given by

$$\gamma_T = \eta_T \left[\frac{B_u \tau_u}{B_d \tau_d} \frac{1}{\eta_u \gamma_u} + \frac{1}{\gamma_d} \right]^{-1} \quad (23)$$

which may be compared to Eq. 8 where the effect of the loss factor η was not yet known. The probability of element error, $P_e(\text{total})$, is computed using this γ_T .

The calculation of P_e , however, is not now done by means of Eqs. 7a and 7b for PSK modulations. These are replaced by more complicated forms taking into account the effects of the phase scintillations on the demodulator performance. Again, the complete analyses are found in the ESL documents previously referenced; here only the results are stated.

For DPSK we first define the amplitude parameter,

$$\alpha \equiv \sqrt{2\gamma} \quad (24)$$

and the variance of the phase difference between successive elements,

$$\sigma_\phi^2 \equiv 2\mu^2 \left[1 - \exp\left(-\frac{\tau}{\tau_D}\right) \right] \quad (25)$$

From this point there are two ways we can go; the ROSCOE model contains both and allows the user to select the one he prefers. If the calculation is desired to be as deterministic as possible, successive values of ϕ are chosen from the zero-mean Gaussian distribution of variance σ_ϕ^2 and substituted directly into the formula for P_e , which now has the form

$$P_e = \frac{1}{2} F(\alpha, \phi) \quad (26a)$$

where

$$F(\alpha, \phi) = 1 - Q\left(\alpha \cos \frac{\phi}{2}, \alpha \sin \frac{\phi}{2}\right) + Q\left(\alpha \sin \frac{\phi}{2}, \alpha \cos \frac{\phi}{2}\right) \quad (26b)$$

$Q(a,b)$ being Marcum's "Q-Function."⁷

The successive values of ϕ used in this expression are computed in such a way as to remain approximately correlated, with a decorrelation time τ_D . This is done by the usual two-point approximation, as follows: let the first value in this sequence, ϕ_1 , be chosen directly from the Gaussian distribution. The second member of the sequence is found by choosing a new ϕ' from the Gaussian distribution and computing the combination

$$\phi_2 = F\phi_1 + \sqrt{1 - F^2} \phi' \quad (27)$$

where

$$F = e^{-\Delta t / \tau_D} \quad (28)$$

Δt being the time interval between sample 1 and sample 2. Succeeding values of ϕ are found by iterating this procedure:

$$\phi_n = F\phi_{n-1} + \sqrt{1 - F^2} \phi' \quad (27')$$

with a new ϕ' (and F if necessary) each time.

If this quasi-deterministic model is not required, a mean value for P_e can be calculated instead by integrating the conditional

probability of error, $P_e(\phi)$, over the ensemble of all possible values of ϕ with their appropriate probabilities, i.e.,

$$\overline{P_e} = \frac{1}{\sqrt{2\pi} \sigma_\phi} \int_0^\infty F(\alpha, \phi) \exp\left[-\frac{\phi^2}{2\sigma_\phi^2}\right] d\phi \quad (29)$$

For CPSK systems the problem is more complicated because it is necessary to consider the phase-locked loop (PLL) in the demodulator. The phase error variance at the demodulator is the sum of two terms:

$$\sigma_\phi^2 = \sigma_{\phi n}^2 + \sigma_{\phi s}^2 \quad (30)$$

where $\sigma_{\phi n}^2$ is the variance due to noise alone in the PLL, and $\sigma_{\phi s}^2$ is the variance due to the phase scintillations in the PLL. It can be shown that

$$\sigma_{\phi n}^2 = \eta^2 \frac{B_L}{\gamma} \left(1 + \frac{B_T}{2\gamma}\right) \quad (31)$$

where B_L is the noise bandwidth of the PLL.

This loop noise bandwidth can be an input quantity, but it is also possible to compute its value in terms of other constants which define the desired operating characteristics of the communication link. Thus, suppose the link has to have a probability of element error given by P_o , and that the RMS phase error in the loop due to noise alone cannot be reduced below σ_n (typically 5° - 10°). In an ideal environment, the fundamental parameter, γ_o , which would be needed in order to achieve the given error rate could be calculated by inverting Eq. 7a in the form

$$P_o = \frac{1}{2} \operatorname{erfc} \sqrt{\gamma_o} \quad (32)$$

Then we can use Eq. 31 to find the desired loop noise bandwidth.

$$B_L = \frac{\gamma_o \sigma_n^2}{\eta_o \tau} \frac{1}{1 + \frac{B\tau}{2\gamma_o}} \quad (33)$$

where η_o is the value of $\eta(B\tau, \tau/\tau_D, \mu)$ when there are no scintillations, i.e., as $\mu \rightarrow 0$ and $\tau_D \rightarrow \infty$.

Now we must find $\sigma_{\phi s}^2$, which can be expressed as an integral in the form

$$\sigma_{\phi s}^2 = \frac{1}{2\pi} \int_{-\infty}^{\infty} |1 - H(j\omega)|^2 S_{\psi}(\omega) d\omega$$

where $H(s)$ is the transfer function of the PLL and $S_{\psi}(\omega)$ is the PSD of the random phase modulation process. The form of $H(s)$, and thus of $\sigma_{\phi s}^2$, depends on the order of the PLL.⁸ In the ROSCOE model the user may specify either a first-order loop or a second-order loop with damping factor ζ . It can then be shown that for a first-order PLL

$$\sigma_{\phi s}^2 = \frac{\mu^2}{1 + 4B_L \tau_D} \quad (34)$$

and for a second-order PLL with damping factor ζ

$$\sigma_{\phi s}^2 = \frac{\mu^2 (1 + aB_L \tau_D)}{1 + bB_L \tau_D + ab(B_L \tau_D)^2} \quad (35)$$

where

$$a \equiv \frac{4}{4\zeta^2 + 1} \quad (36a)$$

and

$$b \equiv \frac{16\zeta^2}{4\zeta^2 + 1} \quad (36b)$$

It ought to be mentioned that the most commonly employed compromise between stability and speed of response in a second-order PLL is to make the damping factor

$$\zeta \equiv 1/\sqrt{2}$$

Having found now the total variance of the PLL phase error, we can relate it to the probability of element error in the following way. It can be shown that the probability density distribution for the phase error of a PLL is

$$p(\phi) = \frac{e^{\alpha \cos \phi}}{2\pi I_0(\alpha)} ; \quad |\phi| \leq \pi \quad (37a)$$

where

$$\alpha \equiv 1/\sigma_\phi^2 \quad (37b)$$

and $I_0(x)$ is the modified Bessel function of the first kind and zero order. This equation is strictly correct only for a first-order PLL when the input is white noise plus a sine wave with Gaussian random phase modulation having the PSD shown in Eq. 17. However, Lindsey⁹ has suggested

that this probability density should be adequate to represent second-order loops, also, in the region where they are usually operated, and uses Eq. 37 for the PLL of either order; we shall do likewise.

Now we can find the probability of element error by combining this with the formula for P_e for a CPSK system, as modified to take into account a phase error, ϕ , namely¹⁰

$$P_e(\phi) = \frac{1}{2} \operatorname{erfc} \left(\sqrt{\gamma} \cos^2 \phi \right) \quad (38)$$

Averaged over the ensemble of possible phase errors, the mean element error probability is given by

$$\overline{P_e} = \frac{1}{2\pi I_o(\alpha)} \int_0^\pi \operatorname{erfc} \left(\sqrt{\gamma} \cos^2 \phi \right) e^{\alpha \cos \phi} d\phi \quad (39)$$

If a quasi-deterministic, single-element value were desired, we could take correlated samples from the distribution of Eq. 37 for substitution into Eq. 38. This option is not available in the present version, but can be added without much difficulty.

6.2 AMPLITUDE SCINTILLATIONS

With respect to the amplitude scintillations caused by a striated medium, a more heuristic approach is unfortunately necessary, because no single theory or explanation is accepted as correct over the whole range of expected conditions. What we are seeking, for the ROSCOE model, is a simple computational algorithm which yields reasonable statistics for the fluctuating signal amplitude at all distances from the near field to the far field (relative to the striated region), and for all values of the phase error variance μ^2 . We find that a great number of research papers have been published on aspects of this problem over the past 20

years. They are very definitely not in complete agreement, often are contradictory. Yet certain results, valid under specific different conditions, do seem to find general acceptance. We have proceeded from these benchmarks to induce an algorithm which agrees with them where they are valid and produces reasonable results when extended to regions where they are invalid. There is no contention here that the algorithm is "correct" or could be rigorously justified, only that it is reasonable and has the right values in limiting cases. Since the experimental measurements themselves have not generally been very precise, we see no need at this time to try for any more rigorous formulation.

The heuristic induction process, while interesting, does not belong to this memorandum and will not be described here. We will present only the necessary preliminaries and quote the conclusions. It may be worth indicating, however, that the sources and starting places for this work are to be found in papers by Mercier,¹¹ Briggs and Parkin,¹² Lawrence, Little, and Chivers,¹³ Singleton,¹⁴ Rino and Fremouw,¹⁵ and Valley.¹⁶

Consider, now, a geometry where the transmitter is located on one side of a striated region (sometimes representable by a "phase screen") at a distance R_1 from it, and the receiver is located on the other side at a distance R_2 . We define a new variable

$$Z \triangleq \frac{R_1 R_2}{R_1 + R_2} \quad (40)$$

We also define a parameter

$$Z_F \triangleq \frac{\pi r_0^2}{2\lambda} \quad (41)$$

where r_o is the transverse scale size of the striations. This Z_F is approximately equal to the "Fresnel distance" for these striations. When the striations are represented as having Chesnut's size distribution with $n = 6$ and parameter σ_o , then it can be shown that $r_o = 2\sigma_o$.

The quantity

$$x \equiv Z/Z_F \quad (42)$$

determines whether we are in the far field ($x \gg 1$), the near field ($x \ll 1$), or as is very often the case, the transition region. In order to make this transition in a smooth manner we introduce the function (not to be confused with Marcum's "Q Function")

$$Q(x) \triangleq \frac{x^2}{1 + x^2} \quad (43)$$

Now suppose that in the absence of striations the signal would have had a fundamental parameter $\gamma = \gamma_1$ at the receiver. When the striations are present the value of γ will be increased and decreased in a time-correlated manner as the line of sight moves across the striations. To begin the computation of γ we define a normalized amplitude,

$$R_o \triangleq \sqrt{\frac{2\gamma_1}{\pi B}} \quad (44)$$

in the absence of striations.

Given that the striations produce phase scintillations with variance μ^2 , we next define the parameter

$$A = \exp\left[-\frac{1}{2} Q(x) \mu^2\right] \quad (45)$$

This is the heart of the heuristic algorithm. The strength of the scintillations is essentially contained in the factor μ^2 , while the factor $Q(x)$ takes care of the dependence on near-field/far-field distance. We introduce the normalized amplitudes

$$P \triangleq AR_0 \quad (46a)$$

and

$$\sigma_T \triangleq \sqrt{1 - A^2} R_0 \quad (46b)$$

Here, P is the amplitude of that portion of the signal which remains in the "specular" component and σ_T represents the "diffracted" component in the sense that σ_T^2 is the variance of this interference term. It will be noted that conservation of energy is satisfied, since $P^2 + \sigma_T^2 \equiv R_0^2$.

Now another complexity enters the picture. It is generally accepted that in the far field the in-phase component (σ_x) and the quadrature component (σ_y) of the "scintillation noise" are equal, i.e., as $x \rightarrow \infty$

$$\sigma_x^2 = \sigma_y^2 = \frac{1}{2} \sigma_T^2,$$

and Rician¹⁷ statistics are valid. At closer distances, there is evidence that more of the energy goes into the quadrature component at the expense of the in-phase component, i.e., for $x < 1$, $\sigma_y^2 > \sigma_x^2$.

To represent this phenomenon we make use of a result due to Valley.¹⁶ Let it be stated at the outset that we do not suppose this theory to be a "correct" representation of the real situation, but only that it provides a convenient approximation which accounts for the transition and is probably as good as the current state of data measurement warrants.

Following Valley, then, we write

$$\sigma_x \equiv \sqrt{H(x)} \sigma_T \quad (47a)$$

and

$$\sigma_y \equiv \sqrt{1 - H(x)} \sigma_T \quad (47b)$$

where

$$H(x) \equiv x f(x) \quad (48)$$

and

$$f(x) \equiv \int_0^{\infty} \frac{\sin t}{t + x} dt \quad (49)$$

This function $f(x)$ is related to the Sine and Cosine Integrals, and its properties are discussed in Sec. 5.2 of the Handbook of Mathematical Functions.¹⁸

Finally, using these values of P , σ_x , σ_y , we compute the normalized output amplitude R and thence the output fundamental parameter γ . If we can ignore the time correlation of successive samples, this is easily done as follows: select random numbers S_x and S_y from zero-mean Gaussian distributions with variances σ_x^2 and σ_y^2 , respectively. Then compute

$$R^2 = (P + S_x)^2 + S_y^2 \quad (50)$$

and

$$\gamma = \frac{\tau_B R^2}{2} \quad (51)$$

In order to include the effects of time correlation, we proceed as previously described for the correlated phase samples (page 23). The first samples, S_{x1} , S_{y1} , are selected as above. Succeeding samples, S_{xn} , S_{yn} , are computed from the formula

$$S_{xn} = F S_{x(n-1)} + \sqrt{1 - F^2} S'_x \quad (52)$$

where

S'_x = the new sample from the Gaussian distribution

$S_{x(n-1)}$ = the prior computed value

and

$$F \equiv \exp(-\Delta t / \tau_D)$$

and its counterpart for S_{yn} .

7 INPUTS

The satellite communications model can be run by setting up the proper FLEXRED "tree" structure in the input stream. The user starts by putting a communication event dataset on the event list, and then satisfies the data input requirements that emanate from this dataset by inputting five further datasets: (1) the uplink dataset, which defines the parameters for the uplink transmitter-receiver pair; (2) the downlink dataset, which contains similar parameters for the downlink; (3) the transmitter platform dataset, which gives the position of the ground transmitter; (4) the satellite platform dataset, which gives the satellite's starting position and orbital parameters (if appropriate); and (5) the receiver platform dataset, which gives the position of the ground receiver. The contents of these datasets are defined in detail in Appendix A.

An example data deck for the communication model was set up to test the code. It was generated by modifying the nominal HIGHALT data deck described in Volume 1. The listing beginning on the next page shows the set of UPDATE change directives used on the ROSCOE DATDEK file to produce the example input deck.

Card 4 introduces a new scale factor for converting inputs in watts to the internally used ergs/second. Cards 6-8 are flags for diagnostic output in the new communications event overlays, and cards 10-12 denote overlay number as a function of event number.

The changes included in cards 13-32 establish the communications outputs and their formats, discussed in Sec. 8. Card 34 is a dataset pointer to the communications event, which places the first communications event on the input event list. Subsequent communications events will be generated by the program, using the time step in the communications event dataset (Card 44).

Cards 37-122 contain the input parameter datasets used by the communication routines. Cards 37-56 constitute the communications event dataset, 57-81 the uplink dataset, 82-106 the downlink dataset, 108-110 the ground transmitter platform dataset, 111-113 the ground receiver platform dataset, and 114-120 the satellite platform dataset. We will discuss these in turn. Card 122 gives the simulation stop time.

DATA DECK MODS FOR SAMPLE COMMUNICATIONS CASE

1	*IDENT CMDSH				
2	*COMPILE HIGHALT				
3	*I HIGHALT,30				
4	WATTS TO ERGS/SEC	WATTS	10000000.		SCALE
5	*I HIGHALT,74				
6	EVENT 22 OUTPUT	NO			
7	EVENT 23 OUTPUT	NO			
8	EVENT 24 OUTPUT	NO			
9	*I HIGHALT,97				
10	EVENT 22 CALLS OVERLAY	22.0	INT		
11	EVENT 23 CALLS OVERLAY	23.0	INT		
12	EVENT 24 CALLS OVERLAY	24.0	INT		
13	*I HIGHALT,114				
14	OC OUTPUT LIST	1.0			ZEROES
15	*I HIGHALT,122				
16	OC OUTPUT FORMAT LIST				REFER
17	*I HIGHALT,150				
18	OC OUTPUT FORMAT LIST				BEG LIST
19	OC OUTPUT FORMAT DATASET				REFER
20	*I HIGHALT,336				
21	OC OUTPUT FORMAT DATASET				BEG SET
22	TYPE OF OUTPUT	OUTCOL			
23	COMMUNICATIONS OUTPUT				TITLE
24	TYPE OF OUTPUT	TYPE	OF OUTPUT		OUTCOL
25	TIME OF OUTPUT	TIME	OF OUTPUT	SEC	OUTCOL
26	UPLINK LOSS FACTOR	UPLINK	LOSS	FACTOR	OUTCOL
27	UPLINK SCINT.	UPLINK	SCINT		OUTCOL
28	DOWNLINK LOSS FACTOR	DOWNLINK	LOSS	FACTOR	OUTCOL
29	DOWNLINK SCINT.	DOWNLINK	SCINT		OUTCOL
30	PROB ERROR-SATELLITE	PROB.	OF ERROR	SATELLITE	OUTCOL
31	PROB ERROR-GROUND	PROB.	OF ERROR	GROUND	OUTCOL
32	PROBABILITY OF ERROR	PROB.	OF ERROR		OUTCOL
33	*I HIGHALT,342				
34	COMMUNICATIONS EVENT DATASET				REFER
35	*O HIGHALT,344,HIGHALT,345				
36	*I HIGHALT,346				
37	* COMMUNICATIONS EVENT DATASETS				PRINT
38	COMMUNICATIONS EVENT DATASET				BEG SET
39	EVENT TYPE	22.	INT		
40	EVENT TIME	1612.	SEC		
41	TRANSMITTER PLATFORM DATASET				REFER
42	SATELLITE PLATFORM DATASET				REFER
43	RECEIVER PLATFORM DATASET				REFER
44	TIME STEP	10.	SEC		
45	TYPE OF MODULATION	DPSK			
46	REGENERATION AT SATELLITE	YES			
47	COHERENT PSK MODULATION	NO			
48	FULLY DETERMINISTIC MODE	NO			
49	CONSTANT ZETA	.707			
50	ORDER OF PHASE LOCKED LOOP	FIRST			

BEST AVAILABLE COPY

51	UPLINK DATASET				REFER
52	DOWNLINK DATASET				REFER
53	SPACE FOR INTERNAL CALCULATIONS	0.0			ZEROS
54	INITIAL VALUE FOR T1	-10.	SEC		
55	INITIAL VALUE FOR T2	-10.	SEC		
56	SPACE FOR INTERNAL CALCULATIONS	9.			ZEROS
57	UPLINK DATASET				REG SET
58	POWER	100.	WATTS		
59	FREQUENCY	8000.	MHZ		
60	TRANSMITTER GAIN	61.	DB		
61	RECEIVER GAIN	16.8	DB		
62	TRANSMITTER LOSS FACTOR	2.5	DB		
63	SYSTEM LINE LOSS FACTOR	0.5	DB		
64	PHASED ARRAY TRANSMITTER	NO			
65	UPLINK XMITR AZIM ERROR	0.	DEG		
66	UPLINK XMITR ELEV ERROR	0.	DEG		
67	SPACE FOR BORESIGHT VECTOR	3.			ZEROS
68	PHASED ARRAY RECEIVER	NO			
69	UPLINK RCVR AZIM ERROR	0.	DEG		
70	UPLINK RCVR ELEV ERROR	0.	DEG		
71	SPACE FOR BORESIGHT VECTOR	3.			ZEROS
72	BIT PERIOD FOR UPLINK	1.0E-8			
73	IF FILTER BANDWIDTH	125.	MHZ		
74	BANDWIDTH FOR PLL	125.	MHZ		
75	BEAMWIDTH	1.5	DEG		
76	SIGNAL-TO-NOISE THRESHOLD	15.	DB		
77	SIDELobe LEVEL	30.	DB		
78	SPACE FOR BIT ERROR, PHASE ERROR	2.0			ZEROS
79	RECEIVER NOISE TEMPERATURE	720.			
80	SPACE FOR NOISE FIGURE, TEMP	2.0			ZEROS
81	SPACE FOR INTERNAL CALCULATIONS	32.			ZEROS
82	DOWNLINK DATASET				REG SET
83	POWER	20.	WATTS		
84	FREQUENCY	7400.	MHZ		
85	TRANSMITTER GAIN	33.2	DB		
86	RECEIVER GAIN	61.	DB		
87	TRANSMITTER LOSS FACTOR	3.4	DB		
88	SYSTEM LOSS FACTOR	0.5	DB		
89	PHASE ARRAY TRANSMITTER	NO			
90	DLINK XMITR AZIM ERROR	0.	DEG		
91	DLINK XMITR ELEV ERROR	0.	DEG		
92	SPACE FOR BORESIGHT VECTOR	3.			ZEROS
93	PHASED ARRAY RECEIVER	NO			
94	DLINK RCVR AZIM ERROR	0.	DEG		
95	DLINK RCVR ELEV ERROR	0.	DEG		
96	SPACE FOR BORESIGHT VECTOR	3.			ZEROS
97	BIT PERIOD FOR DOWNLINK	1.0E-8			
98	IF FILTER BANDWIDTH	125.	MHZ		
99	BANDWIDTH FOR PLL	125.	MHZ		
100	BEAMWIDTH	1.5	DEG		
101	SIGNAL-TO-NOISE THRESHOLD	15.	DB		
102	SIDELobe LEVEL	30.	DB		
103	SPACE FOR BIT ERROR, PHASE ERROR	2.0			ZEROS
104	RECEIVER NOISE TEMPERATURE	200.			
105	SPACE FOR NOISE FIGURE, TEMP	2.0			ZEROS
106	SPACE FOR INTERNAL CALCULATIONS	32.			ZEROS
107	* TRANSMITTER, RECEIVER, AND SATELLITE POSITIONS				PRINT
108	TRANSMITTER PLATFORM DATASET				REG SET
109	TYPE OF PLATFORM	FIXED			
110	POSITION	0.0	-79.33	47.75	GEOGR
111	RECEIVER PLATFORM DATASET				REG SET
112	TYPE OF PLATFORM	FIXED			
113	POSITION	0.0	-83.	42.5	GEOGR
114	SATELLITE PLATFORM DATASET				REG SET
115	TYPE OF PLATFORM	CIRCULAR			
116	INCLINATION	90.	DEG		
117	LONGITUDE	-79.33	DEG		
118	ARG. OF POINT-OF-INTEREST	47.75	DEG		
119	TIME AT POINT-OF-INTEREST	1600.	SEC		
120	PERIOD	6650.	SEC		
121	* HIGHALT, 305				
122	STOP TIME	1721.	SEC		

Communications Event Dataset (Cards 37-56)

- 39 Event type (always 22 with current model)
- 40 Event time for first communication event
- 41-43 Pointers to ground transmitter, satellite, and ground receiver platform datasets
- 44 Time step between subsequent communication events
- 45 Modulation type (CPSK for coherent phase shift keying, DPSK for differential phase shift keying, or FSK for frequency shift **keying**)
- 46 Regeneration flag (YES for signal regeneration at satellite, NO if not)
- 47 Coherent FSK flag (YES for coherent FSK modulation, NO otherwise)
- 48 Fully deterministic mode flag (YES for fully deterministic simulation, NO otherwise--see Section 6)
- 49 Constant zeta (a constant used in the second-order PLL mode, currently set to 0.707)
- 50 Order of PLL (FIRST for first-order phase-locked loop, SECOND for second-order)
- 51-52 Pointers to the uplink and downlink datasets
- 53 Space for six variables computed internally (input 6.0 zeros)
- 54 Initial value of $T1^*$ (set to -10 on input for initialization)
- 55 Initial value of $T2$ (set to -10)
- 56 Space for nine internal variables (input 9.0 zeros)

Uplink Dataset (Cards 57-81)

- 58 Transmitter power
- 59 Transmitter frequency
- 60 Transmitter gain
- 61 Receiver gain
- 62 Transmitter loss factor (between transmitter and its antenna)

* $T1$ and $T2$ are used internally for keeping track of the times at which data samples are taken (for time correlation purposes).

- 63 System line loss between satellite antenna and satellite transponder's IF amplifier
- 64 Phased array transmitter flag (YES for phased array, NO otherwise)
- 65-66 Azimuth and elevation pointing errors of transmitter antenna
- 67 Space for transmitter antenna boresight (enter 3.0 zeros)
- 68 Phased array receiver flag (YES for phased array, NO otherwise)
- 69-70 Azimuth and elevation pointing errors of receiver antenna
- 71 Space for receiver antenna boresight (enter 3.0 zeros)
- 72 Bit period for uplink
- 73 IF filter bandwidth
- 74 Bandwidth for phase locked loop
- 75 Beamwidth of transmitter antenna
- 76 Signal-to-noise threshold for accepting signals
- 77 Receiver sidelobe level
- 78 Space for bit error and phase error computed internally (input 2.0 zeros)
- 79 Receiver noise temperature (enter value here or enter noise figure and physical temperature of receiver in the next two words)
- 80 Spaces for noise figure and physical temperature (enter 2.0 zeros if noise temperature is input above)
- 81 Spaces for internal calculations (enter 32.0 zeros)

Downlink Dataset (Cards 82-106)

Same type of data as for the uplink dataset

Transmitter Platform Dataset (Cards 108-110)

- 109 Type of platform (enter FIXED for a platform fixed with respect to the earth. Other options are CIRCULAR for circular orbits, ORBITAL or ELLIPTICAL for elliptic orbits)
- 110 Position of the fixed platform (Note: other types require additional inputs (see descriptions of datasets P1, P2, P3, and P4 in Appendix A)

Receiver Platform Dataset (Cards 111-113)

- 112 Type of platform
- 113 Position of the fixed platform

Satellite Platform Dataset (Cards 114-120)

- 115 Type of platform (CIRCULAR orbit)
- 116 Orbital inclination
- 117 Longitude of satellite's ascending node at time of arrival
 at reference point-of-interest
- 118 Earth-centered angular travel of satellite past its
 ascending node at reference point-of-interest
- 119 Time of arrival of satellite at reference point-of-interest
- 120 Orbital period of satellite

8 OUTPUTS

A single output table has been constructed to display the communication results. The OUTCOL format described in Volume 1 of this manual is used; it sets up a maximum of ten column headings and displays any variables the user specifies, in the format defined in the input deck.

For the communication model these outputs are given:

Column 1	<u>Type of Output.</u> Program prints the message COM-RECEVD if the communications are received, or UP-LIMITED or DN-LIMITED if the signal noise drops below a specified threshold in either the uplink or downlink direction.
Column 2	<u>Time of Output.</u> The engagement time for this line of output.
Column 3	<u>Uplink Loss Factor.</u> Uplink propagation loss factor (dB)
Column 4	<u>Uplink Scintillation.</u> Standard deviation of phase scintillations affecting uplink (rad)
Column 5	<u>Downlink Loss Factor.</u> Downlink propagation loss factor (dB)
Column 6	<u>Downlink Scintillation.</u> Standard deviation of phase scintillations affecting downlink (rad)
Column 7	<u>Probability of Error Satellite.</u> Probability of element error in received signal demodulated at the satellite (for regenerative systems only)
Column 8	<u>Probability of Error Ground.</u> Probability of element error in received signal demodulated at the ground after regeneration at the satellite
Column 9	<u>Probability of Error.</u> Probability of element error in received signal

The output produced by running the HIGHALT data deck (Vol. 1) with the modifications described in the preceding section is shown on the next page. The simulation starts at a time 1612 seconds with the first communications event. A large burst goes off at 1620 seconds, directly above the transmitter. Forty seconds later, the satellite passes over the transmitter.

The communication outputs show that the burst disrupts the uplink signal for about 20-30 seconds because of severe absorption. Later scintillation effects cause continued severe degradation of communication reliability.

COMMUNICATIONS OUTPUT

TYPE OF OUTPUT	TIME OF OUTPUT SEC	UPLINK LOSS FACTOR	UPLINK SCINT	DOWNLINK LOSS FACTOR	DOWNLINK SCINT	PROB. OF ERROR SATELLITE	PROB. OF ERROR GROUND	PROB. OF ERROR
COMMRECEVD	1612,000	1,001	0.	1,005	0.	0.	0.	0.
UP-LIMITED	1622,000	*****	.15246E+08	0,000	0.	.50000	.50000	.50000
UP-LIMITED	1632,000	*****	.99177E+07	0,000	0.	.50000	.50000	.50000
COMMRECEVD	1642,000	41,841	.30454E+06	1,005	.17919E+04	.49896	0.	.49896
COMMRECEVD	1652,000	1,825	46801.	1,013	466,52	.23744	.87895E+17	.23744
COMMRECEVD	1662,000	1,241	65493.	1,659	11099.	.39805	.49802	.49960
COMMRECEVD	1672,000	1,243	.18955E+06	1,694	28181.	.49911	.29279	.49963
COMMRECEVD	1682,000	1,604	.70896E+06	1,703	74310.	.49569	.11933	.49667
COMMRECEVD	1692,000	1,121	.15559E+06	1,718	.11024E+06	.46409	.16213	.47973
COMMRECEVD	1702,000	1,094	.12131E+06	1,725	.11363E+06	.92345E+01	.42329	.43766
COMMRECEVD	1712,000	1,079	.45690E+06	1,732	.11238E+06	.45308	.82870E+01	.46086

REFERENCES

1. Schwartz, Bennett, and Stein, Communication Systems and Techniques, McGraw-Hill (1966), Chapter 7.
2. J.R. Garbarino, The ROSCOE Manual, Vol. 1, "Program Description," General Research Corporation CR-1-520, August 1975.
3. J. Marshall and P. Hu, A Computer Code for the Prediction of Satellite Communication System Performance in a Nuclear Environment (SATL) (U), ESL, Inc., ESL-TM241, 1 March 1972, Sec. 4.
4. D.C. Hogg and W.W. Mumford, "The Effective Noise Temperature of the Sky," Microwave Journal, 3, March 1960, pp. 80-84.
5. J. Roberts, et al., PSK Satellite Communication Systems in a Nuclear Environment (U), ESL Incorporated ESL-TM391 (DNA 3289T), 26 October 1973 (CONFIDENTIAL). ✓
6. V. Mower, et al., Noncoherent PSK Satellite Communication Systems in a Nuclear Environment (U), ESL Incorporated ESL-TM504 (DNA 3529T), 6 September 1974 (SECRET FORMERLY RESTRICTED DATA). ✓
7. Reference 1, Appendix A.
8. A.J. Viterbi, Principles of Coherent Communication, McGraw-Hill (1966), Chapter 2.
9. W.C. Lindsey, "Phase-Shift-Keyed Signal Detection With Noisy Reference Signals," IEEE Transactions on Aerospace and Electronic Systems, 2, July 1966, pp. 393-401.
10. Reference 1, p. 304.
11. R.P. Mercier, "Diffraction by a Screen Causing Large Random Phase Fluctuations," Proc. Camb. Phil. Soc., 58, pp. 383-400 (1962).
12. B.H. Briggs and I.A. Parkin, "On the Variation of Radio Star and Satellite Scintillations With Zenith Angle," J. Atmos. & Terr. Phys., 25, pp. 339-365 (1963).
13. R.S. Lawrence, C.G. Little, and H.J.H. Chivers, "A Survey of Ionospheric Effects Upon Earth-Space Radio Propagation," Proc. IEEE, 52, pp. 4-27 (1964).

REFERENCES (Cont.)

14. D.G. Singleton, "Saturation and Focusing Effects in Radio-Star and Satellite Scintillations," J. Atmos. and Terr. Phys., 32, pp. 187-208 (1970).
15. C.L. Rino and E.J. Fremouw, "Statistics for Ionospherically Diffracted VHF/UHF Signals," Radio Science, 8, pp. 223-233 (1973).
16. G.C. Valley, "The Relation Between the Specular to Interference Ratio and the Scintillation Index," IEEE Trans. Comm., COM-23, pp. 1351-1354 (1975).
17. S.O. Rice, "Mathematical Analysis of Random Noise," Bell System Tech. J., 23, 282-332 (July 1944), and 24, 46-156 (January 1945); [esp. Sec. 3.10].
18. M. Abramowitz and I.A. Stegun (Ed.), Handbook of Mathematical Functions, Dover Publications (1965).

APPENDIX A

COMMUNICATIONS DATASETS

The following pages contain the "DSCRIP" cards for datasets which are of direct use for communications cases. DSCRIP cards are discussed in Vol. 3 of this manual. The C3, CU, CD, OC, and P4 datasets are new, having been added to the basic ROSCOE DSCRIP file for the communications version of the code. The P1, P2, and P3 datasets are not new; they are included here only because they represent alternate modes of platform input for communications cases.

DESCRIPTION OF DATASETS USED IN COMMUNICATIONS CASES

```

*/ -----
*/
*/      C3 DATASET (COMMUNICATIONS EVENT)
*/
*/ -----
NEW C3      COMMUNICATIONS EVENT DATASET
I  KTYPE    EVENT TYPE (#22)
R  TIME     TIME OF THIS EVENT
DSP PLATT   POINTER TO TRANSMITTER PLATFORM DATASET
DSP PLATS   POINTER TO SATELLITE PLATFORM DATASET
DSP PLATR   POINTER TO RECEIVER PLATFORM DATASET
R  TSTEP    TIME STEP FOR COMMUNICATION EVENTS
H  TYPE     ENTER==CP8K,DP8K,FSK==FOR COMMUNICATIONS TYPE
H  REGEN    FLAG==YES==FOR REGENERATION AT SATELLITE
H  COM      FLAG==YES==FOR FSK COHERENT MODE
H  DET      FLAG==YES==FOR FULLY DETERMINISTIC MODE
R  ZETA     A CONSTANT
H  PLL      ENTER==FIRST,SECOND==FOR ORDER OF PHASE LOCKED LOOP
DSP DSPCU   POINTER TO UPLINK DATASET
DSP DSPCD   POINTER TO DOWNLINK DATASET
DSP DSPDC   POINTER TO OUTPUT DATASET
I  IFLAG    EVENT FLAG (SET #0 INITIALLY)
R4 CTH      OFF-AXIS BORESIGHT ANGLES
R  T1       STORED MEASUREMENT TIME
R  T2       LAST MEASUREMENT TIME
R  PHIU     UPLINK PHASE AT LAST MEASUREMENT TIME
R  PHID     DOWNLINK PHASE AT LAST MEASUREMENT TIME
R  PHIT     TOTAL PATH PHASE AT LAST MEASUREMENT TIME
R  SXU      UPLINK SIGMA IN X AT LAST TIME
R  SYU      UPLINK SIGMA IN Y AT LAST TIME
R  SXD      DOWNLINK SIGMA IN X AT LAST TIME
R  SYD      DOWNLINK SIGMA IN Y AT LAST TIME
R  TNEW1    NEW (MEASUREMENT = 1) TIME
R  TNEW2    NEW (MEASUREMENT = 2) TIME
*/
*/
*/ -----
*/
*/      C4 DATASET (UPLINK DATASET)
*/
*/ -----
NEW C4      COMMUNICATIONS UPLINK DATASET
R  POWER    TRANSMITTED POWER
R  FREQ      FREQUENCY
R  GT       ON-AXIS GAIN OF TRANSMITTER
R  GR       ON-AXIS GAIN OF RECEIVER
R  XLU1      TRANSMITTER LOSS FACTOR
R  XLU2      SYSTEM (LINE) LOSS BETWEEN SATELLITE ANTENNA AND AMPLIFIER
H  ARRAY    ENTER==YES==FOR PHASED ARRAY TRANSMITTER
R  TAZER     TRANSMITTER BORESIGHT AZIMUTH ERROR

```


DESCRIPTION OF DATASETS USED IN COMMUNICATIONS CASES

```

R3 BVECR      BORESIGHT VECTOR OF RECEIVER
R  TAUD      BIT PERIOD FOR DOWNLINK
R  RD        IF FILTER BANDWIDTH OF GROUND RECEIVER
R  HLG       NOISE BANDWIDTH OF GROUND RECEIVER (PLL MODE)
R  BEAMR     RECEIVER BEAMWIDTH
R  SN        SIGNAL-TO-NOISE THRESHOLD
R  SL        SIDELobe LEVEL
R  PD        DESIRED BIT ERROR RATE AT GROUND
R  SIGN      RMS PHASE ERROR DUE TO NOISE IN THE GROUND RECEIVER
              (ENTER EITHER HLG OR PD AND SIGN)
R  TRG       RECEIVER NOISE TEMPERATURE
R  NRG       RECEIVER NOISE FIGURE
R  TPG       PHYSICAL TEMPERATURE OF GROUND RECEIVER
              (ENTER EITHER TPG OR NRG, TPG OPTIONAL)
R  SDD       SIGNAL PARAMETER FOR DOWNLINK
R  TND       NOMINAL SYSTEM NOISE TEMPERATURE FOR DOWNLINK
R  R         RANGE TO GROUND RECEIVER
R3 XLOSD     DOWNLINK LINE OF SIGHT
R  GAMO      DOWNLINK SIGNAL PARAMETER
R3 POS       POSITION OF TRANSMITTER
R10 STATT    TRANSMITTER STATE(SATELLITE)
R10 STATR    RECEIVER STATE(GROUND)
R  XD        DOWNLINK BANDWIDTH /TIME PRODUCT
R  XLFD      DOWNLINK MISMATCH LOSS FACTOR
*/
*/
*/ -----
*/
*/      OC DATASET (OUTPUT DATASET FOR COMMUNICATIONS)
*/
*/ -----

```

```

NEW OC      OUTPUT DATASET FOR COMMUNICATIONS
M  TYPE     FLAG FOR MEASUREMENT TYPE (UP=LIMITED,DN=LIMITED,
              COM=RECEVD)
R  TIME     TIME OF OUTPUT
R  TN       UPLINK OR DOWNLINK SYSTEM TEMPERATURE
R  XLPU     UPLINK PROPAGATION LOSS FACTOR
R  XLDU     UPLINK DISPERSIVE LOSS FACTOR
R  TAU      UPLINK ANTENNA NOISE TEMPERATURE
R  XMU      DEVIATION OF PHASE SCINTILLATIONS IN UPLINK
R  TDU      DECORRELATION TIME FOR SCINTILLATIONS IN UPLINK
R  XLPD     DOWNLINK PROPAGATION LOSS FACTOR
R  XLDD     DOWNLINK DISPERSIVE LOSS FACTOR
R  TAD      DOWNLINK ANTENNA NOISE TEMPERATURE
R  XMD      DEVIATION OF PHASE SCINTILLATIONS IN DOWNLINK
R  TDD      DECORRELATION TIME FOR SCINTILLATIONS IN DOWNLINK
R  PES      PROBABILITY OF ELEMENT ERROR IN SIGNAL AT SATELLITE
R  PEG      PROBABILITY OF ELEMENT ERROR IN SIGNAL AT GROUND
R  PE       PROBABILITY OF ELEMENT ERROR IN SIGNAL FOR TOTAL PATH
R  XMT      DEVIATION OF PHASE SCINTILLATIONS FOR TOTAL PATH

```


DESCRIPTION OF DATASETS USED IN COMMUNICATIONS CASES

```

R   TDY      DECORRELATION TIME FOR SCINTILLATIONS FOR TOTAL PATH
*/
*/
*/ -----
*/
*/   P1 DATASET (FIXED PLATFORM)
*/
*/ -----
NEW P1      PLATFORM TYPE=1 (FIXED) DATASET
M   KTYPE   PLATFORM TYPE (ALWAYS =FIXED= FOR A FIXED PLATFORM)
R3  POS     PLATFORM POSITION
*/
*/
*/ -----
*/
*/   P2 DATASET (ELLIPTIC ORBIT PLATFORM)
*/
*/ -----
NEW P2      PLATFORM TYPE 2 == TRAID ORBITAL ELEMENTS
M   KTYPE   PLATFORM MODEL TYPE ( = THORBITAL )
R10 ORBEL   A TRAID 10=VECTOR OF ORBITAL ELEMENTS
*/
*/
*/ -----
*/
*/   P3 DATASET (CIRCULAR ORBIT PLATFORM)
*/
*/ -----
NEW P3      PLATFORM TYPE 3 FOR CIRCULAR ORBITS
M   KTYPE   PLATFORM MODEL TYPE ( = BMCIRCULAR )
R   AINC    INCLINATION OF ORBITAL PLANE
R   ALONG   LONGITUDE OF ASCENDING NODE (AS CALCULATED AT TIME BELOW)
R   OLOC    LOCATION IN ORBIT (AROUND FROM ASCENDING NODE)
R   TIME    TIME OF VALIDITY OF GIVEN DATA
R   PERI    PERIOD OF ORBIT
*/
*/
*/ -----
*/
*/   P4 DATASET (ORBITAL PLATFORM = CONVERTED TO P2 DATASET INTERNALLY)
*/
*/ -----
NEW P4      POSITION DATASET FOR SATELLITES (ELLIPTICAL ORBITS)
M   KTYPE   TYPE OF POSITION CALCULATION ( = ELLIPTICAL IN THIS CASE)
R   PERD    ORBITAL PERIOD OF SATELLITE
R   AINC    INCLINATION ANGLE OF ORBITAL PLANE
R   ASCN    LONGITUDE OF ASCENDING NODE (AT T = 0)
R   ARGP    ARGUMENT OF PERIGEE
R   PERAL   PERIGEE ALTITUDE
R   TMPER   TIME OF PERIGEE PASSAGE

```

APPENDIX B

MODIFICATIONS TO PROGRAM STRUCTURE

Development of the communications version of ROSCOE required modifications to nine routines: COLLF, EVPROC, FUZINC, OUTRTN, PLTFRM, POTSOL, REFRCT, REFIS, and ROSCOE. In addition, 27 new routines were added and three new overlays were required. Additional datasets were added; these are described in Appendix A. This appendix contains flow charts and definitions of symbols for the key routines of the communication model.

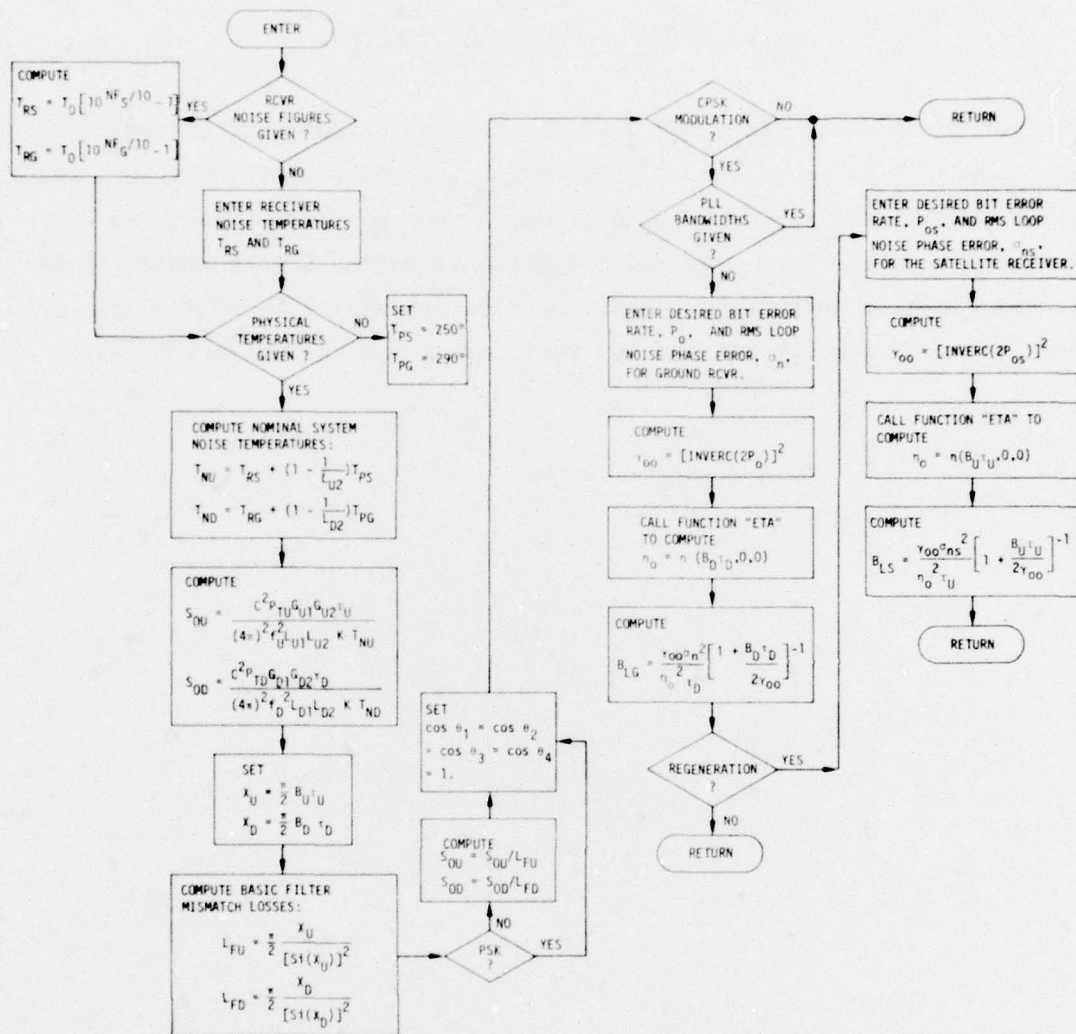


Figure B.1. Flow Diagram for Subroutine COMIN--Communication Initialization Routine

Definition of Symbols in Subroutine COMIN (Communications Initialization)

T_{RS}	Receiver noise temperature of satellite receiver, °K
T_{RG}	Receiver noise temperature of ground receiver, °K
T_o	Standard reference temperature = 290°K
\overline{NF}_S	Receiver noise figure for satellite receiver, dB
\overline{NF}_G	Receiver noise figure for ground receiver, dB
T_{PS}	Physical temperature of satellite receiver front end and transmission lines (default value = 250°K)
T_{PG}	Physical temperature of ground receiver front end and transmission lines (default value = 290°K)
T_{NU}	Nominal system noise temperature for uplink (satellite receiver)
T_{ND}	Nominal system noise temperature for downlink (ground receiver)
L_{U2}	System (line) loss between satellite receiving antenna and satellite transponder's IF amplifier
L_{D2}	System (line) loss between ground receiving antenna and ground receiver's IF amplifier
S_{OU}	Precomputable signal parameter for the uplink signal received at satellite
S_{OD}	Precomputable signal parameter for the downlink signal received at ground terminal
γ	"Gamma," a fundamental parameter for digital communications systems, defined as E_b/N_o , the ratio of total average received energy per signal element (bit) to noise power per unit bandwidth
C	Speed of light
P_{TU}	Total average radiated RF power at ground-terminal transmitting antenna

P_{TD}	Total average radiated RF power at satellite transmitting antenna (corrected for any "backoff" which may be required by a Frequency Division Multiple Access (FDMA) system to prevent serious intermodulation distortion)
G_{U1}	On-axis gain of ground transmitting antenna beam
G_{U2}	On-axis gain of satellite receiving antenna beam
G_{D1}	On-axis gain of satellite transmitting antenna beam
G_{D2}	On-axis gain of ground receiving antenna beam
τ_U	Bit period (element length) for uplink, s
τ_D	Bit period (element length) for downlink, s
f_U	Frequency of ground-transmitted (uplink) RF signal, Hz
f_D	Frequency of satellite-transmitted (downlink) RF signal, Hz
L_{U1}	System loss between ground transmitter and its antenna
L_{D1}	System loss between satellite transmitter and its antenna
K	Boltzmann's constant = 1.380622×10^{-23} J/°K
B_U	IF filter bandwidth of satellite receiver
B_D	IF filter bandwidth of ground receiver
L_{FU}	Filter mismatch loss at satellite receiver, due to using a (rectangular) bandpass filter rather than a matched one
L_{FD}	Filter mismatch loss at ground receiver
$Si(X)$	Integral function $\int_0^X (\sin t)/t dt$
θ_J	Antenna pointing angle off boresight for antenna type J (initialized to zero here) <ul style="list-style-type: none"> • $\theta_J \equiv 0$ always for steered dish antennas • $J = 1$, ground transmitting antenna; $J = 2$, satellite receiving antenna; $J = 3$, satellite transmitting antenna; $J = 4$, ground receiving antenna

CPSK	"Coherent phase-shift keying" modulation
PLL	"Phase locked loop" used in demodulating a CPSK signal
P_o	Desired bit error rate for communication system, evaluated at the ground receiver
σ_n	RMS phase error due to noise in ground receiver's PLL, rad
γ_{oo}	"Gamma" (measured just prior to the receiver's demodulator in the absence of scintillations) required to produce bit error rate P_o for the CPSK system
η_o	Parameter computed by Function ETA, evaluated here in the absence of scintillations
B_{LG}	Noise bandwidth of ground receiver's PLL, Hz
P_{os}	Desired bit error rate at the satellite receiver if regeneration is being employed
σ_{ns}	RMS phase error due to noise in satellite receiver's PLL if regeneration is being employed, rad
B_{LS}	Noise bandwidth of satellite receiver's PLL if regeneration is being employed, Hz

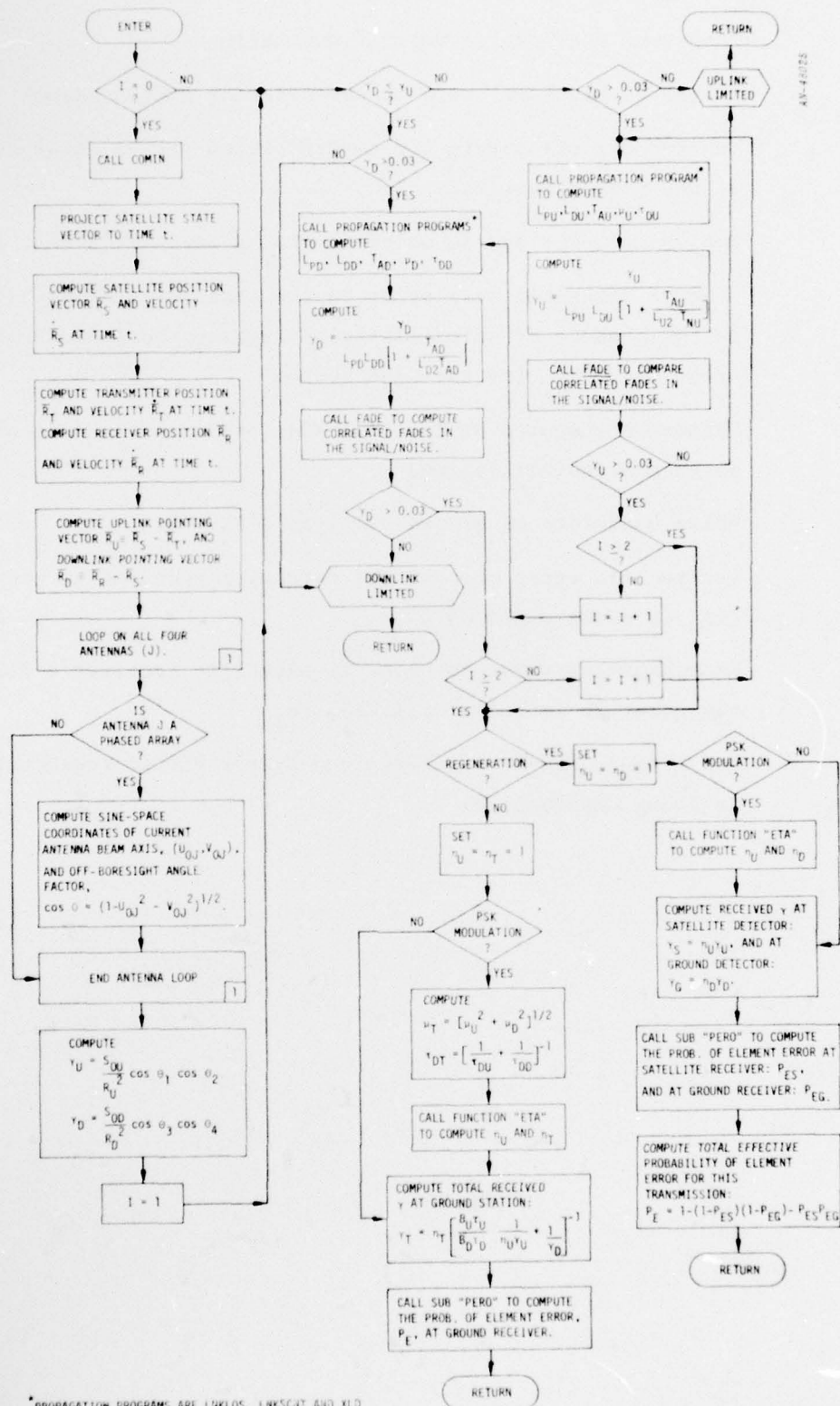


Figure B.2. Flow Diagram for Program COMLINK--Communications Event Program

Definition of Symbols in Program COMLINK

t	Simulated time of this communications event
\overline{R}_S	Position vector of satellite at time t
$\dot{\overline{R}}_S$	Velocity vector of satellite at time t
\overline{R}_T	Position vector of ground transmitting antenna at time t
$\dot{\overline{R}}_T$	Velocity vector of ground transmitting antenna at time t
\overline{R}_R	Position vector of ground receiving antenna at time t
$\dot{\overline{R}}_R$	Velocity vector of ground receiving antenna at time t
\overline{R}_U	Uplink pointing vector from ground transmitter to satellite at time t
\overline{R}_D	Downlink pointing vector from satellite to ground receiver at time t
J	Antenna designator: <ul style="list-style-type: none"> $J = 1$, ground transmitting antenna; $J = 2$, satellite receiving antenna; $J = 3$, satellite transmitting antenna; $J = 4$, ground receiving antenna
U_{OJ}, V_{OJ}	Sine-space coordinates of current axis of antenna beam pattern for antenna J ($= (0,0)$ for non-phased array antennas)
θ_J	See definitions for Subroutine COMIN
γ_U	Ratio of bit energy to noise power density for uplink
γ_D	Ratio of bit energy to noise power density for downlink
S_{OU}, S_{OD}	Precomputed constants; see definitions for Subroutine COMIN
R_U	Uplink range from ground transmitter to satellite $= \overline{R}_U $
R_D	Downlink range from satellite to ground receiver $= \overline{R}_D $
L_{PD}	Downlink propagation loss factor (ratio)
L_{DD}	Downlink dispersive loss factor (ratio)

T_{AD}	Downlink antenna noise temperature, °K (measured in ground receiving antenna)
μ_D	Standard deviation of phase scintillations affecting downlink, rad (assumed: zero-mean, Gaussian random phase process)
τ_{DD}	Decorrelation time for scintillations affecting downlink, s
L_{D2}	See definitions for Subroutine COMIN
L_{PU}	Uplink propagation loss factor (ratio)
L_{DU}	Uplink dispersive loss factor (ratio)
T_{AU}	Uplink antenna noise temperature, °K (measured in satellite receiving antenna)
μ_U	Standard deviation of phase scintillations affecting uplink, rad
τ_{DU}	Decorrelation time for scintillations affecting uplink, s
L_{U2}	See definitions for Subroutine COMIN
η_U	Parameter η (see below) computed for uplink path: $\eta(B_U \tau_U, \tau_U / \tau_{DU}, \mu_U)$
η_D	Parameter η (see below) computed for downlink path: $\eta(B_D \tau_D, \tau_D / \tau_{DD}, \mu_D)$
η_T	Parameter η (see below) computed for total path: $\eta(B_D \tau_D, \tau_D / \tau_{DT}, \mu_T)$
PSK	Phase-shift keying
μ_T	Standard deviation of phase scintillations affecting total path, rad
τ_{DT}	Decorrelation time for scintillations affecting total path, s
η	Fundamental factor relating to phase scintillations affecting PSK modulated signals; defined to be proportional to the integral of the power spectral density function of phase-distorted signal after passing through the IF filter

γ_T	Ratio of bit energy to noise power density for total path, computed just prior to ground receiver's detector
P_E	Probability of element error in received signal
γ_S	Ratio of bit energy to noise power density computed just prior to satellite receiver's detector (regenerative systems only)
γ_G	Ratio of bit energy to noise power density for downlink path, computed just prior to ground receiver's detector (regenerative systems only)
P_{ES}	Probability of element error in received signal demodulated at the satellite (regenerative systems only)
P_{EG}	Probability of element error in received signal demodulated at the ground after regeneration at the satellite

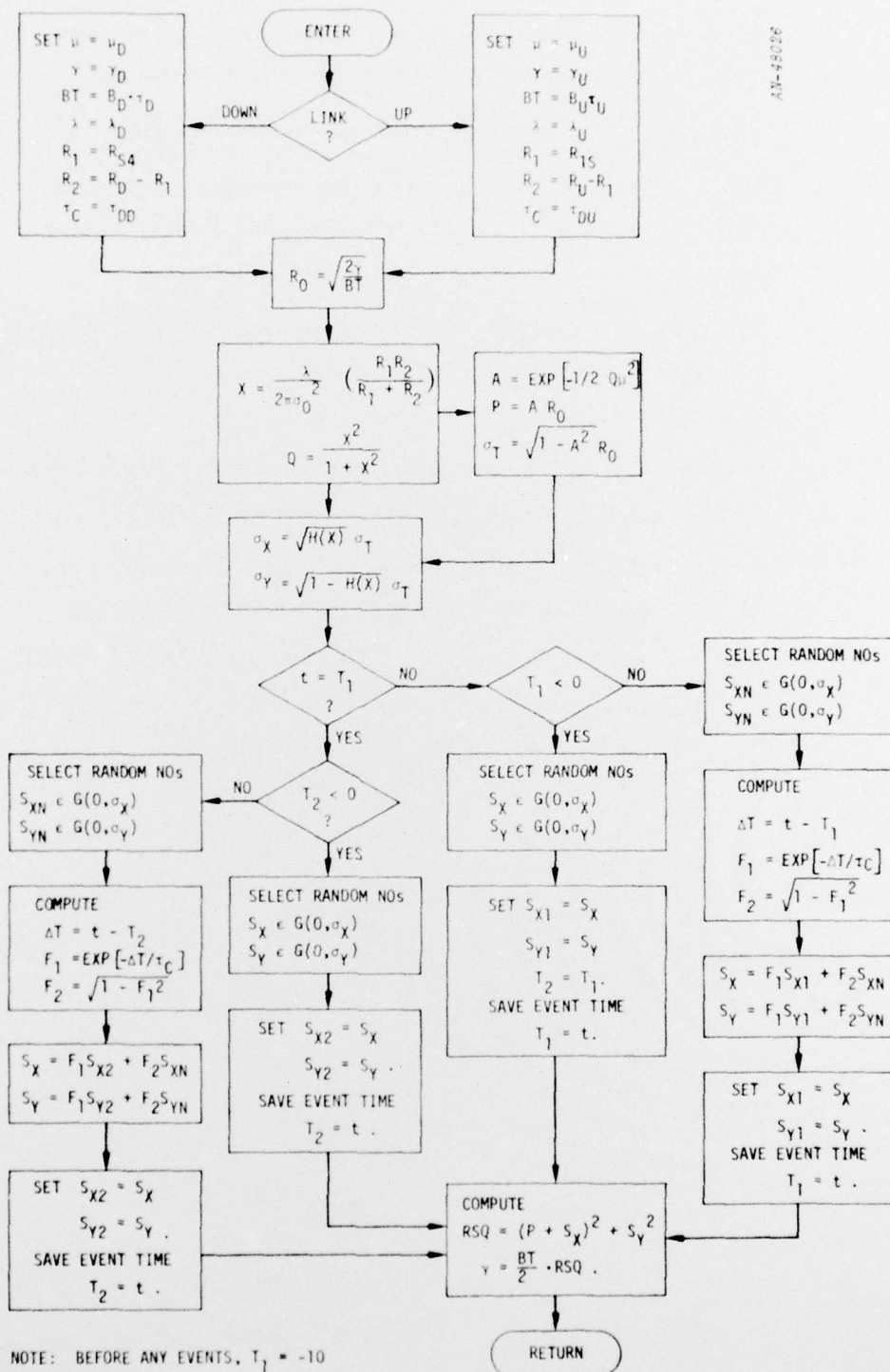
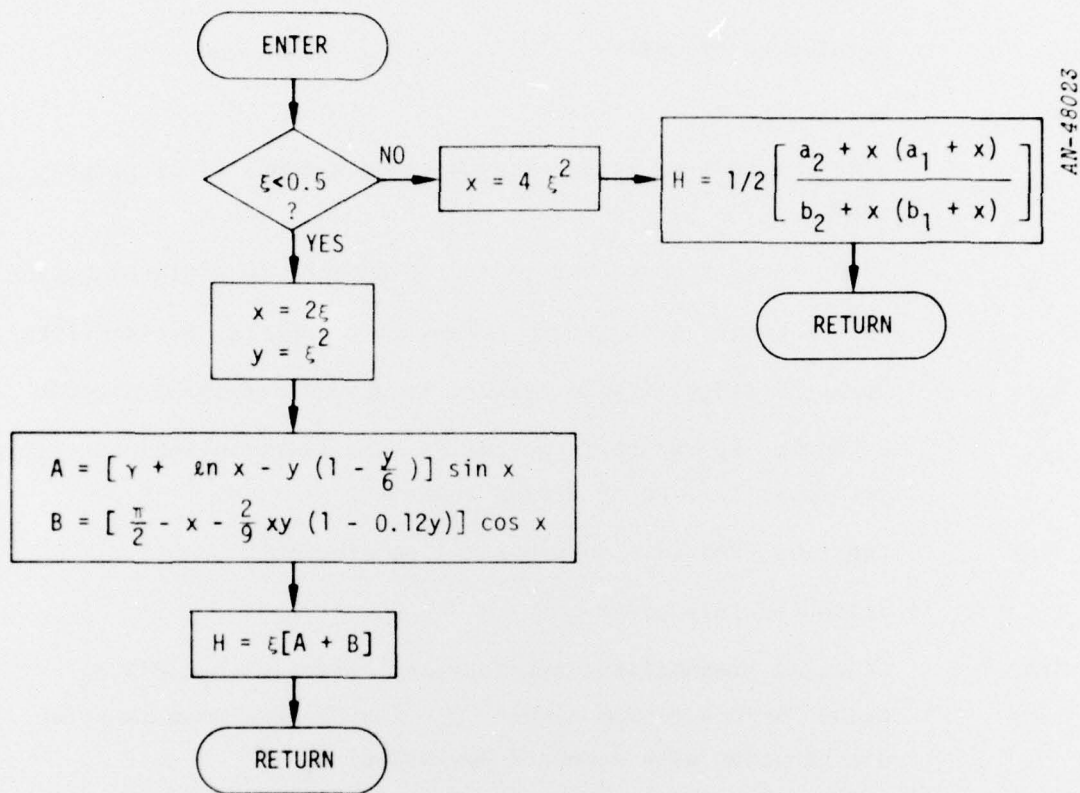


Figure B.3. Flow Diagram for Subroutine FADE--Computes Correlated Fades

Definition of Symbols in Subroutine FADE

μ	Standard deviation of phase scintillations affecting this link, rad
λ_U	Wavelength of uplink
λ_D	Wavelength of downlink
R_{1S}	Slant range from ground transmitting antenna to striated region
R_{S4}	Slant range from ground receiving antenna to striated region
R_U	Uplink range, from ground transmitting antenna to satellite
R_D	Downlink range, from satellite to ground receiving antenna
σ_0	Parameter appearing in striation size distribution; currently set equal to 1 km in a DATA statement
$H(X)$	Function HFUN (see subprogram flow diagram)
t	"time" of this event
$G(m, \sigma)$	Gaussian probability distribution; notation $S_X \in G(0, \sigma_X)$ means "draw a random number S_X from a zero-mean Gaussian distribution with standard deviation σ_X ."
T_1	Stored measurement time for time correlation calculations
T_2	Last measurement time for time correlation calculations



WHERE: $a_1 = 7.241163$ $a_2 = 2.463936$
 $b_1 = 9.068580$ $b_2 = 7.157433$
 $\gamma = 0.5772156649$

Figure B.4. Flow Diagram for Function HFUN

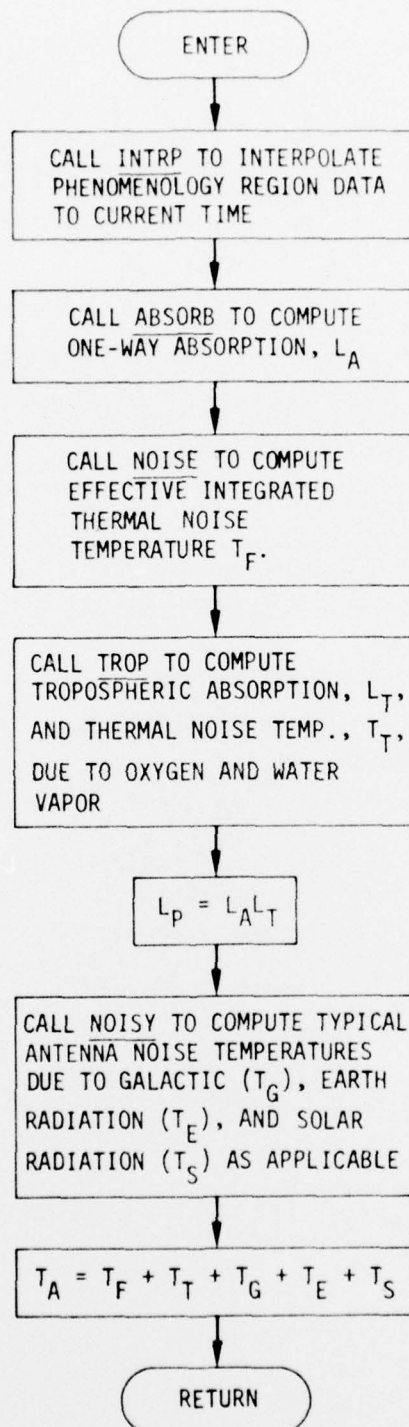
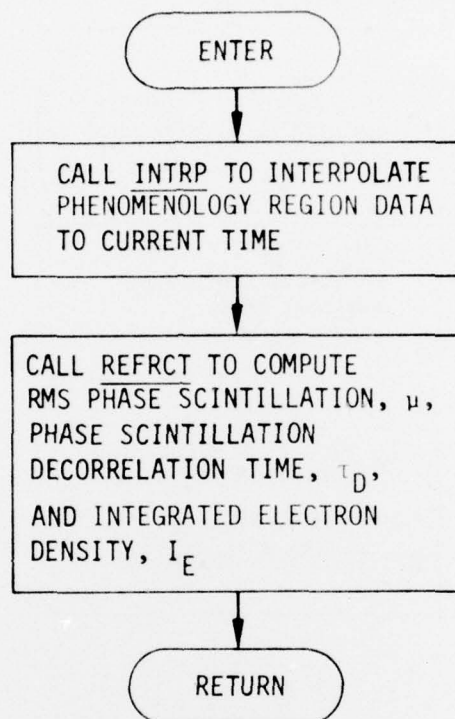


Figure B.5. Flow Diagram for Program LNKLOS--Computes Absorption and Noise Losses



AN-48021

Figure B.6. Flow Diagram for Program LNKSCNT--Computes Scintillation Effects

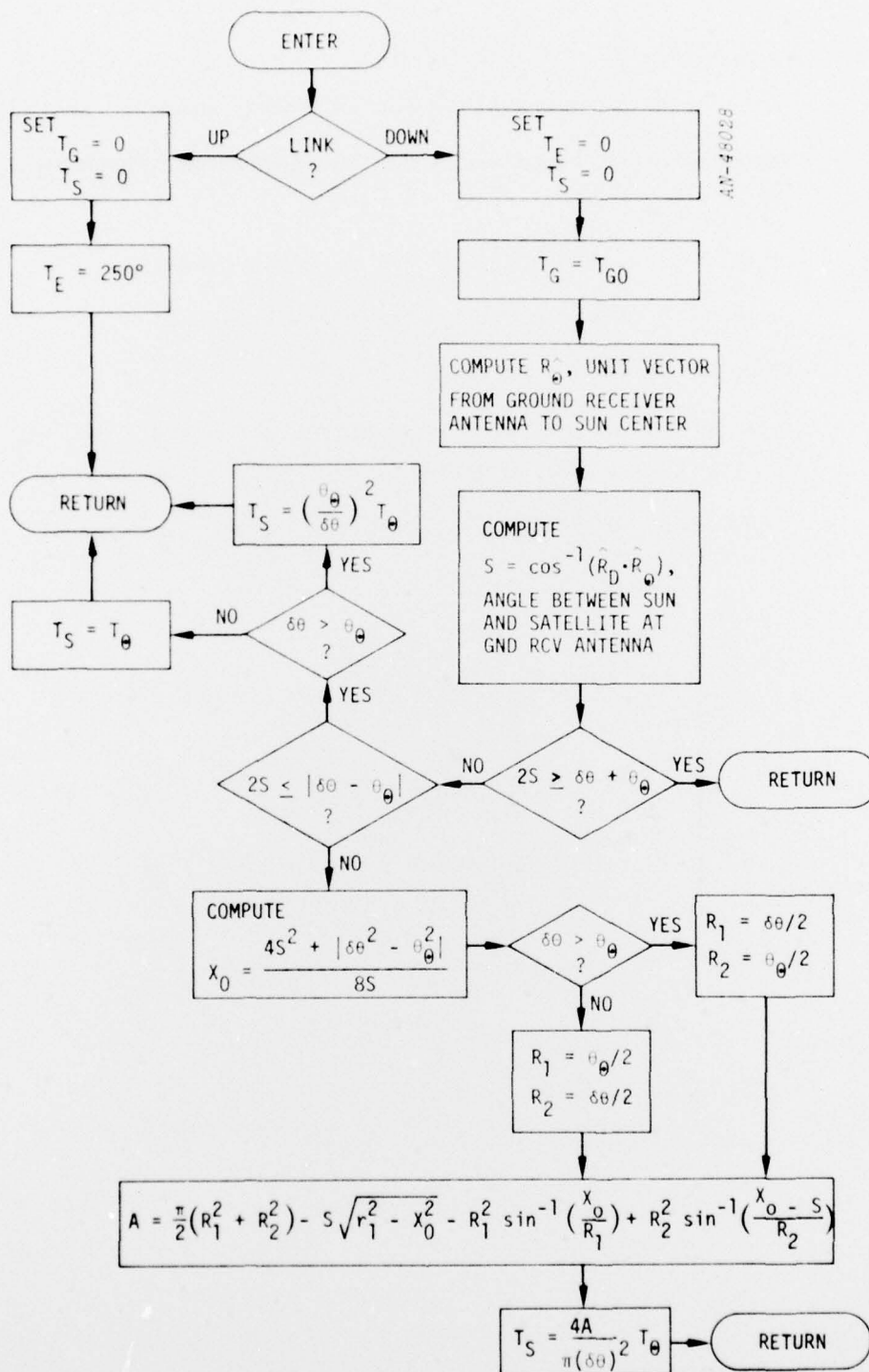


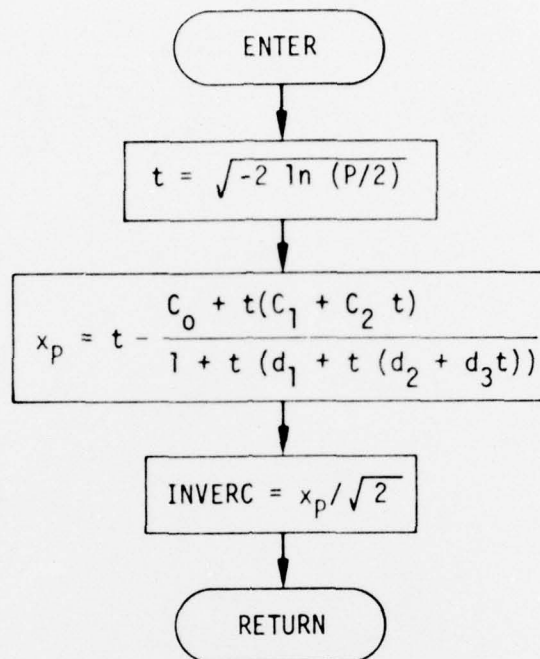
Figure B.7. Flow Diagram for Subroutine NOISY--Computes Antenna Noise Temperatures

Definition of Symbols for Subroutine NOISY

T_G	Antenna noise temperature due to (mean) galactic sources, °K
T_E	Antenna noise temperature due to (estimated) earth radiation , °K
T_S	Antenna noise temperature due to solar radiation, °K
$\delta\theta$	Beamwidth of the ground receiving antenna
θ_\odot	Angular diameter of the sun = 0.5°
T_{GO}	Average galactic noise temperature, °K [*] = $2.6 \times 10^{19} / f_D^2$ where f_D = downlink RF frequency, Hz
T_\odot	Equivalent noise temperature of the quiet sun [*]

$$T_\odot = \begin{cases} \frac{2.0 \times 10^{14}}{f_D} & \text{if } f_D < 2.5 \times 10^8 \text{ or } f_D > 3.5 \times 10^{10} \text{ Hz} \\ \frac{2.0 \times 10^{14}}{f_D} \left\{ 1 + \frac{1}{2.3} \sin 2\pi \left[\frac{\log_{10} 6(f_D \times 10^{-9} - 0.10)}{2.3} \right] \right\} & \text{if } 2.5 \times 10^8 \leq f_D \leq 3.5 \times 10^{10} \text{ Hz} \end{cases}$$

^{*} Precomputed during "initialization" and stored in a list.



CONSTANTS

$C_0 = 2.515517$	$d_1 = 1.432788$
$C_1 = 0.802853$	$d_2 = 0.189269$
$C_2 = 0.010328$	$d_3 = 0.001308$

Source: Abramowitz & Stegun, 26.2.23.

Figure B.8. Flow Diagram for Function INVERC--Inverts the Error Function ERFC (Z)

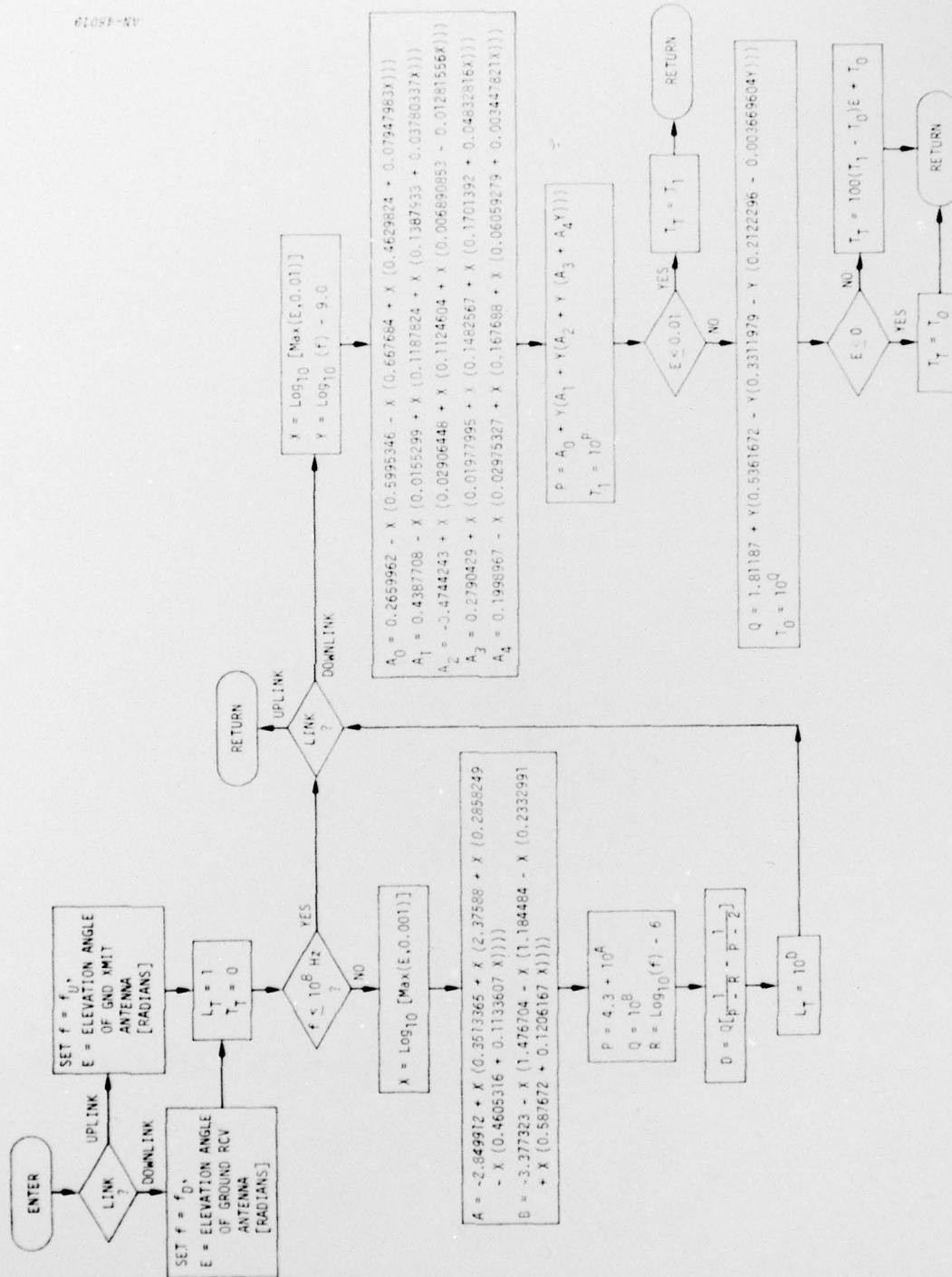
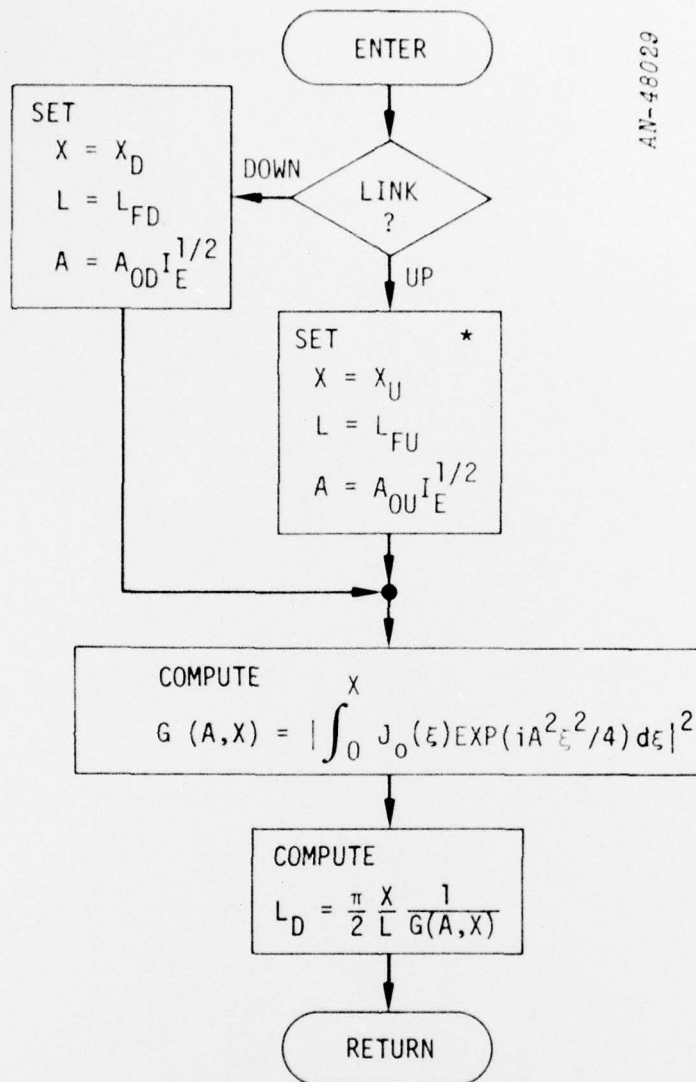


Figure B.10. Flow Diagram for Subroutine TROP--Computes Tropospheric Absorption



* X_U , X_D , L_{FU} , L_{FD} are real quantities which were computed in "INITIALIZATION".

$$A_{OU} = \frac{0.0585}{f_U^{3/2} \tau_U}, \quad A_{OD} = \frac{0.0585}{f_D^{3/2} \tau_D}$$

Figure B.11. Flow Diagram for Subroutine XLD--Computes Dispersive Loss

DISTRIBUTION LIST

DEPARTMENT OF DEFENSE

Director
Defense Advanced Rsch. Proj. Agency
ATTN: STO

Defense Communication Engineer Center
ATTN: Code R410, James W. McLean

Director
Defense Communications Agency
ATTN: Code 480

Defense Documentation Center
Cameron Station
12cy ATTN: TC

Director
Defense Nuclear Agency
ATTN: TISI, Archives
ATTN: DDST
ATTN: RAAE
3cy ATTN: TITL, Tech. Library

Dir. of Defense Rsch. & Engineering
ATTN: S&SS (OS)

Commander
Field Command
Defense Nuclear Agency
ATTN: FCPR

Director
Interservice Nuclear Weapons School
ATTN: Document Control

Director
Joint Strat. Tgt. Planning Staff, JCS
ATTN: JPST, Captain G. D. Goetz

Chief
Livermore Division Fld. Command, DNA
Lawrence Livermore Laboratory
ATTN: FCPL

DEPARTMENT OF THE ARMY

Commander/Director
Atmospheric Sciences Laboratory
U.S. Army Electronics Command
ATTN: DRSEL-BL-SY-S, F. E. Niles

Director
BMD Advanced Tech. Ctr.
Huntsville Office
ATTN: ATC-T, Melvin T. Capps

Commander
Harry Diamond Laboratories
ATTN: DRXDO-NP, Francis N. Wimenitz
ATTN: DRXDO-TI
ATTN: DRXDO-NP

Director
TRASANA
ATTN: R. E. DeKinder, Jr.

DEPARTMENT OF THE ARMY (Continued)

Director
U.S. Army Ballistic Research Labs.
ATTN: Mark D. Kregel
ATTN: Lawrence J. Puckett

Commander
U.S. Army Foreign Science & Tech. Ctr.
ATTN: P. A. Crowley

Commander
U.S. Army Missile Command
ATTN: DRSMI-XS, Chief Scientist

Commander
U.S. Army Missile Intelligence Agency
ATTN: Jim Gamble

Commander
U.S. Army Nuclear Agency
ATTN: MONA-WE, J. Berberet

DEPARTMENT OF THE NAVY

Chief of Naval Operations
ATTN: Alexander Brandt

Commander
Naval Ocean Systems Center
3cy ATTN: Code 2200, Verne E. Hildebrand

Director
Naval Research Laboratory
ATTN: Code 7701, Jack D. Brown
ATTN: Code 7750, S. Ossakow

Officer-In-Charge
Naval Surface Weapons Center
ATTN: Code WX21, Tech. Lib.
ATTN: Code WA501, Navy Nuc. Prgms. Off.

Director
Strategic Systems Project Office
ATTN: NSSP-2722, Fred Wimberly
ATTN: NSP-2722, Marcus Meserole

DEPARTMENT OF THE AIR FORCE

AF Geophysics Laboratory, AFSC
ATTN: OPR, Harold Gardner
ATTN: OPR, James C. Ulwick
ATTN: OPR, Alva T. Stair

AF Weapons Laboratory, AFSC
ATTN: DYT, Capt L. Wittwer
ATTN: SUL
ATTN: NSS, John M. Kamm
ATTN: DYT, Capt Mark S. Fry

HQ USAF/RD
ATTN: RDQSM

Commander
Rome Air Development Center, AFSC
ATTN: EMTLD, Doc. Library

DEPARTMENT OF THE AIR FORCE (Continued)

SAMSO/SZ

ATTN: SZJ, Major Lawrence Doan

Commander In Chief

Strategic Air Command

ATTN: ADWATE, Capt Bruce Bauer

ATTN: XPFS, Maj Brian G. Stephan

Headquarters USAF/SA

ATTN: AFSA, Capt Henkle

ENERGY RESEARCH & DEVELOPMENT ADMINISTRATION

University of California

Lawrence Livermore Laboratory

ATTN: Ralph S. Hager, L-31

ATTN: Donald R. Dunn, L-156

Los Alamos Scientific Laboratory

ATTN: Doc. Con. for Eric Jones

ATTN: Doc. Con. for John Zinn

Sandia Laboratories

ATTN: Tech. Lib. Processes Station

OTHER GOVERNMENT AGENCY

Department of Commerce

Office of Telecommunications

Institute for Telecom. Science

ATTN: William F. Utlaut

DEPARTMENT OF DEFENSE CONTRACTORS

Aerospace Corporation

ATTN: Norman D. Stockwell

ATTN: Doug Rowcliffe

Brown Engineering Company, Inc.

Cummings Research Park

ATTN: Romeo A. Deliberis

ATTN: James E. Cato

ATTN: Joel D. Bigley

ESL, Inc.

ATTN: C. W. Prettie

ATTN: James Marshall

General Electric Company

Tempo-Center for Advanced Studies

ATTN: DASIAC

ATTN: Tim Stephens

ATTN: Warren S. Knapp

DEPARTMENT OF DEFENSE CONTRACTORS (Continued)

General Research Corporation

ATTN: John Ise, Jr.

ATTN: Joel Garbarino

ATTN: H. S. Ostrowsky

ATTN: J. J. Baltes

Jaycor

ATTN: S. R. Goldman

Johns Hopkins University

Applied Physics Laboratory

ATTN: Document Librarian

Lockheed Missiles & Space Co., Inc.

ATTN: D. R. Churchill

M.I.T. Lincoln Laboratory

ATTN: Lib. A-082 for David M. Towle

Martin Marietta Aerospace

Orlando Division

ATTN: Roy W. Heffner

Mission Research Corporation

ATTN: R. Hendrick

ATTN: R. Bogusch

ATTN: D. Sappenfield

ATTN: Russell Christian

Physical Dynamics, Inc.

ATTN: Joseph B. Workman

R & D Associates

ATTN: Bryan Gabbard

ATTN: Robert E. LeLevier

Science Applications, Inc.

ATTN: D. Sachs

ATTN: Curtis A. Smith

ATTN: Daniel A. Hamlin

Science Applications, Inc.

ATTN: Dale H. Divis

ATTN: Noel R. Byrn

Stanford Research Institute

ATTN: Walter G. Chesnut

ATTN: Ray L. Leadabrand

Visidyne, Inc.

ATTN: J. W. Carpenter

ATTN: Charles Humphrey